

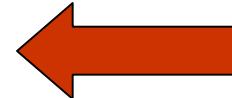


8 GeV Multi- Mission Injector Linac

G. William Foster

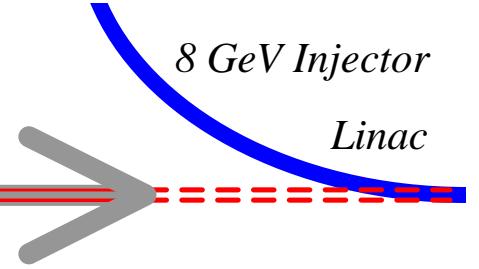
Proton Driver II Design Study



- Initiated by Fermilab Directorate
- Goal is 5x more protons in Main Injector.
- Side-by-side studies (*including cost*) of:
 - 8 GeV Booster Synchrotron
 - *8 GeV Superconducting Linac* 
 - Main Injector modifications for $I_{BEAM} \sim 2$ Amp

FNAL needs a “Main Injector Sized” project ~2005

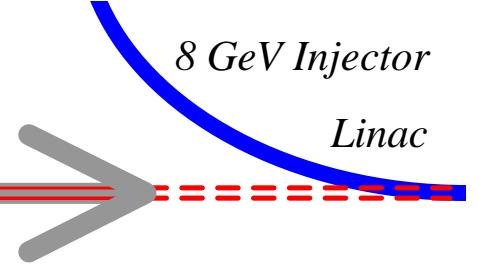
OUTLINE



- 8 GeV Linac Concept
- Primary Parameters
- Technical Subsystems
- Cost Estimate
- Other Missions for 8 GeV Linac
- Concluding Remarks



8 GeV Injector Linac Concept



1) Copy SNS Linac up to 1.2 GeV

(Reduced beam current and relaxed schedule allow some design optimizations)

2) Use “TESLA” Cryomodules from $1.2 \rightarrow 8 \text{ GeV}$

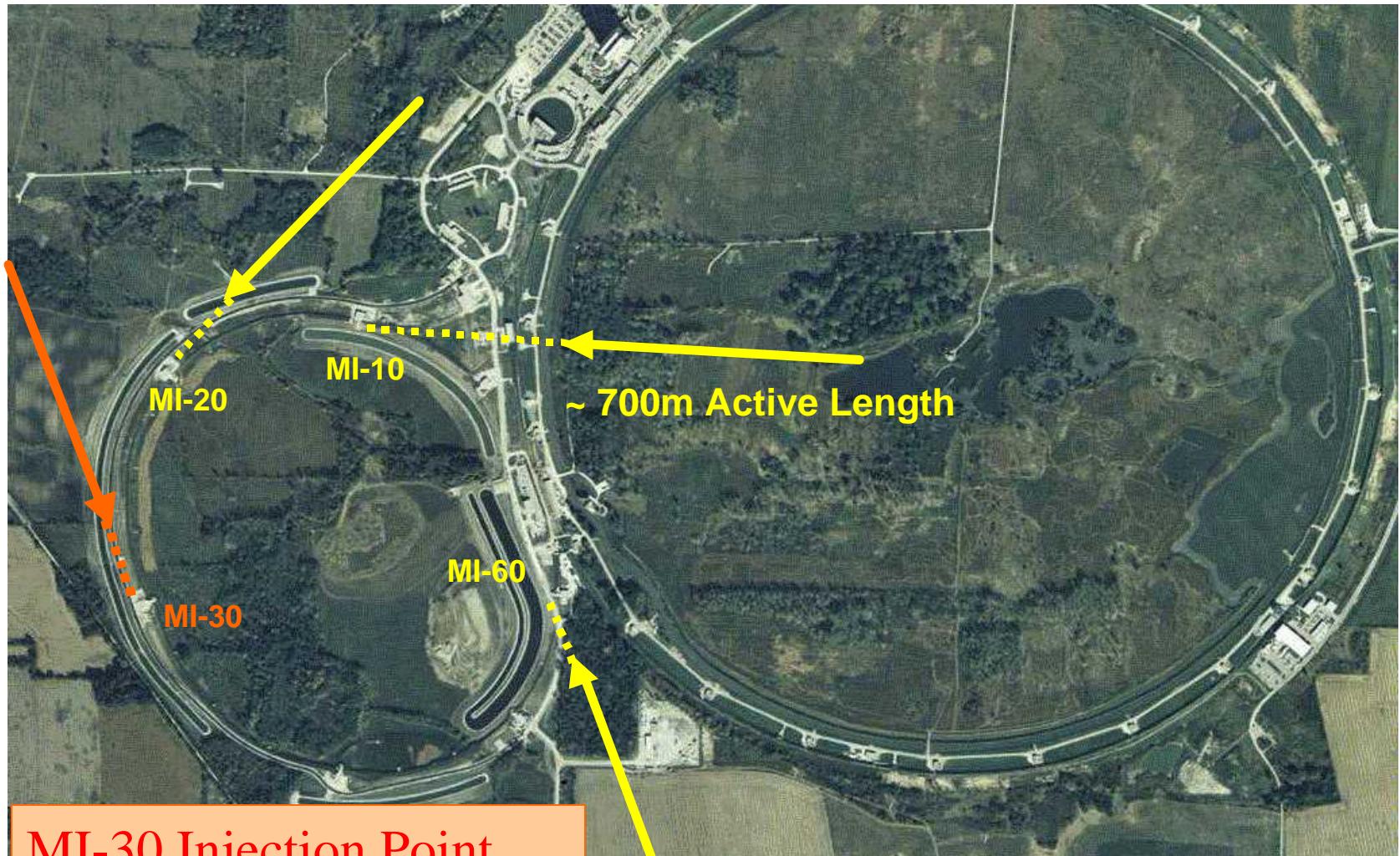
3) H⁻ Injection at 8 GeV in Fermilab Main Injector

⇒ “Super-Beams” in Main Injector:

2 MW Beam power, small emittances, and minimum (1.5 sec) cycle time

- Other possible missions for unused linac cycles:
 - 8 GeV ν program, 8 GeV electrons ==> XFEL, etc.

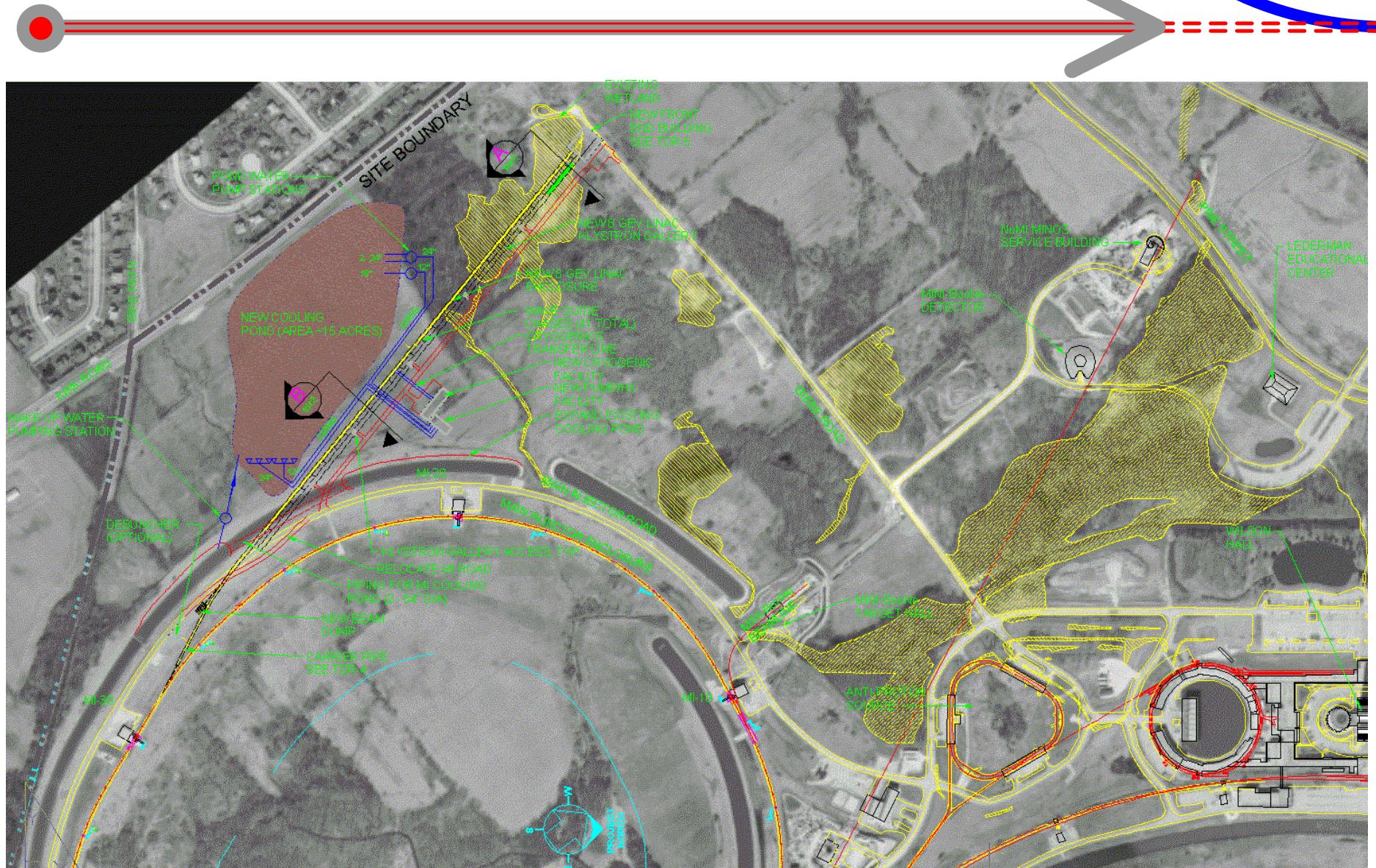
8 GeV Injector Linac - Possible Sitings



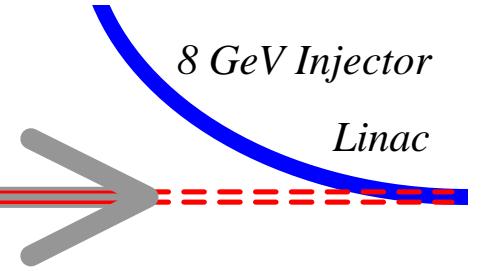
MI-30 Injection Point
Chosen for Design Study

8 GeV Linac Siting for Design Study

8 GeV Injector
Linac



8 GeV Linac Parameters



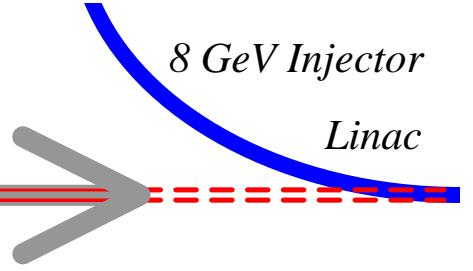
8 GeV LINAC

Energy	GeV	8
Particle Type	H- Ions, Protons , or Electrons	
Rep. Rate	Hz	10
Active Length	m	671
Beam Current	mA	25
Pulse Length	msec	1
Beam Intensity	P / pulse	1.5E+14 (can be H-, P, or e-)
	P/hour	5.4E+18
Linac Beam Power	MW avg.	2
	MW peak	200

MAIN INJECTOR WITH 8 GeV LINAC

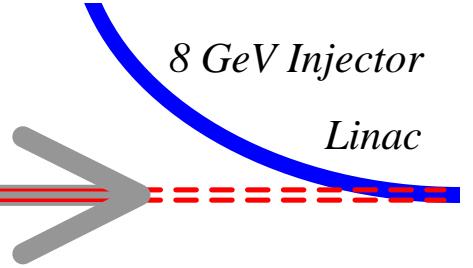
MI Beam Energy	GeV	120	
MI Beam Power	MW	2.0	
MI Cycle Time	sec	1.5	filling time = 1 msec
MI Protons/cycle		1.5E+14	5x design
MI Protons/hr	P / hr	3.6E+17	
H-minus Injection	turns	90	SNS = 1060 turns
MI Beam Current	mA	2250	

Benefits of 8 GeV Injector



- Benefits to V and Fixed-Target program
 - solves proton economics problem: > 5E18 Protons/hr at 8 GeV
 - operate MI with small emittances, high currents, and low losses
- Benefits to Linear Collider R&D
 - 1.5% scale demonstration of TESLA economics
 - Evades the Linear Collider R & D funding cap
 - Simplifies the Linear Collider technology choice
 - Establishes stronger US position in LC technology
- Benefits to Muon Collider / n-Factory R&D
 - Establishes cost basis for P-driver and muon acceleration
- Benefits to VLHC: small emittances, high Luminosity
 - ~4x lower beam current reduces stored energy in beam
 - Stage 1: reduces instabilities, allows small beam pipes & magnets
 - Stage 2: injection at final synchrotron-damped emittances

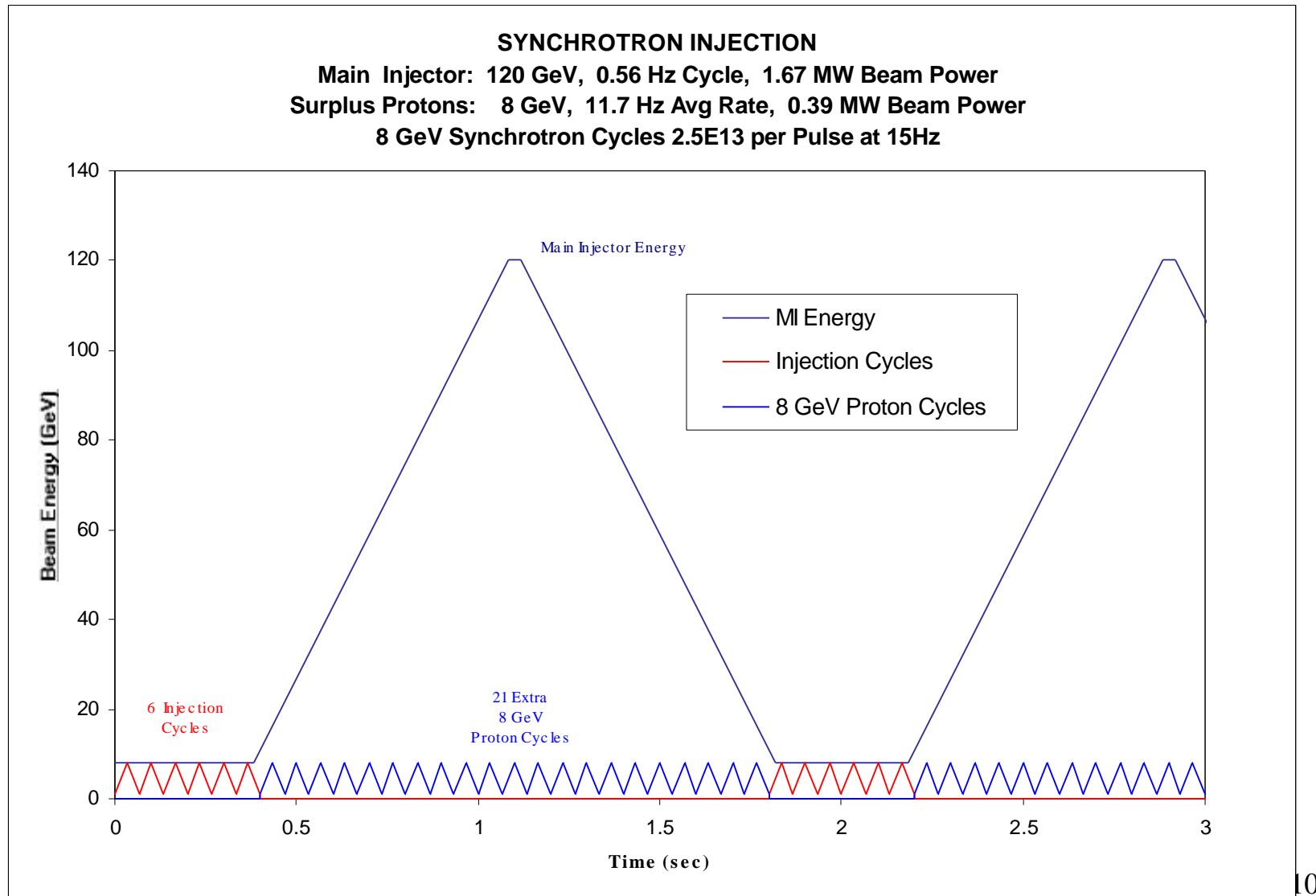
Main Injector with 8 GeV Linac



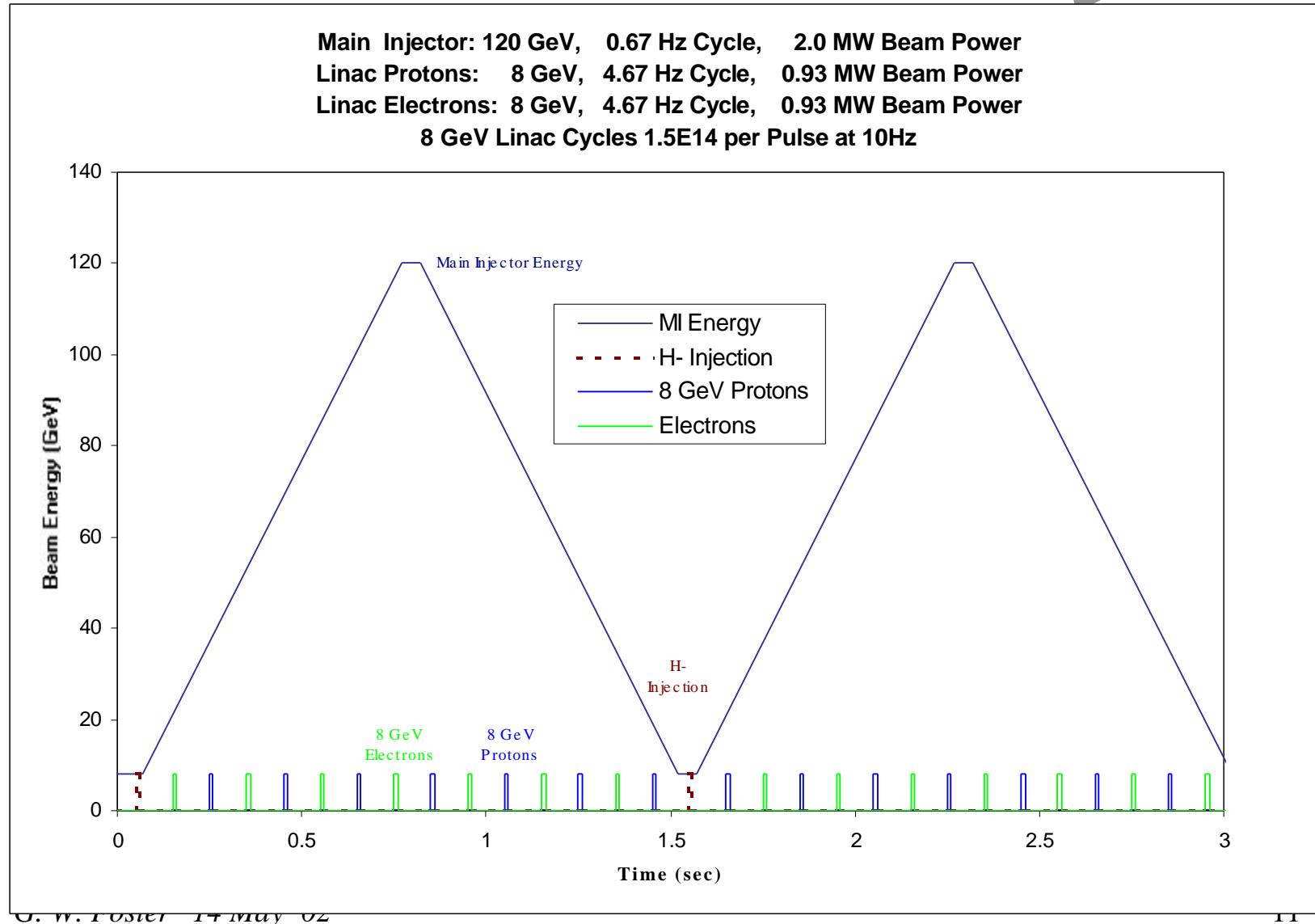
- 1.5 Second Cycle time to 120 GeV
 - filling time 1 msec or less
 - no delay for multiple Booster Batches
 - no beam gaps for “Booster Batches” -- only Abort gap
- H⁻ stripping injection at 8 GeV
 - 25 mA linac beam current
 - 90-turn Injection gives MI Beam Current ~2.3 A
(SNS has 1060 turn injection at 1 GeV)
 - preserve linac emittances ~ 0.5π (95%) at low currents
 - phase space painting needed at high currents

② *can put a frightening amount of beam in MI*

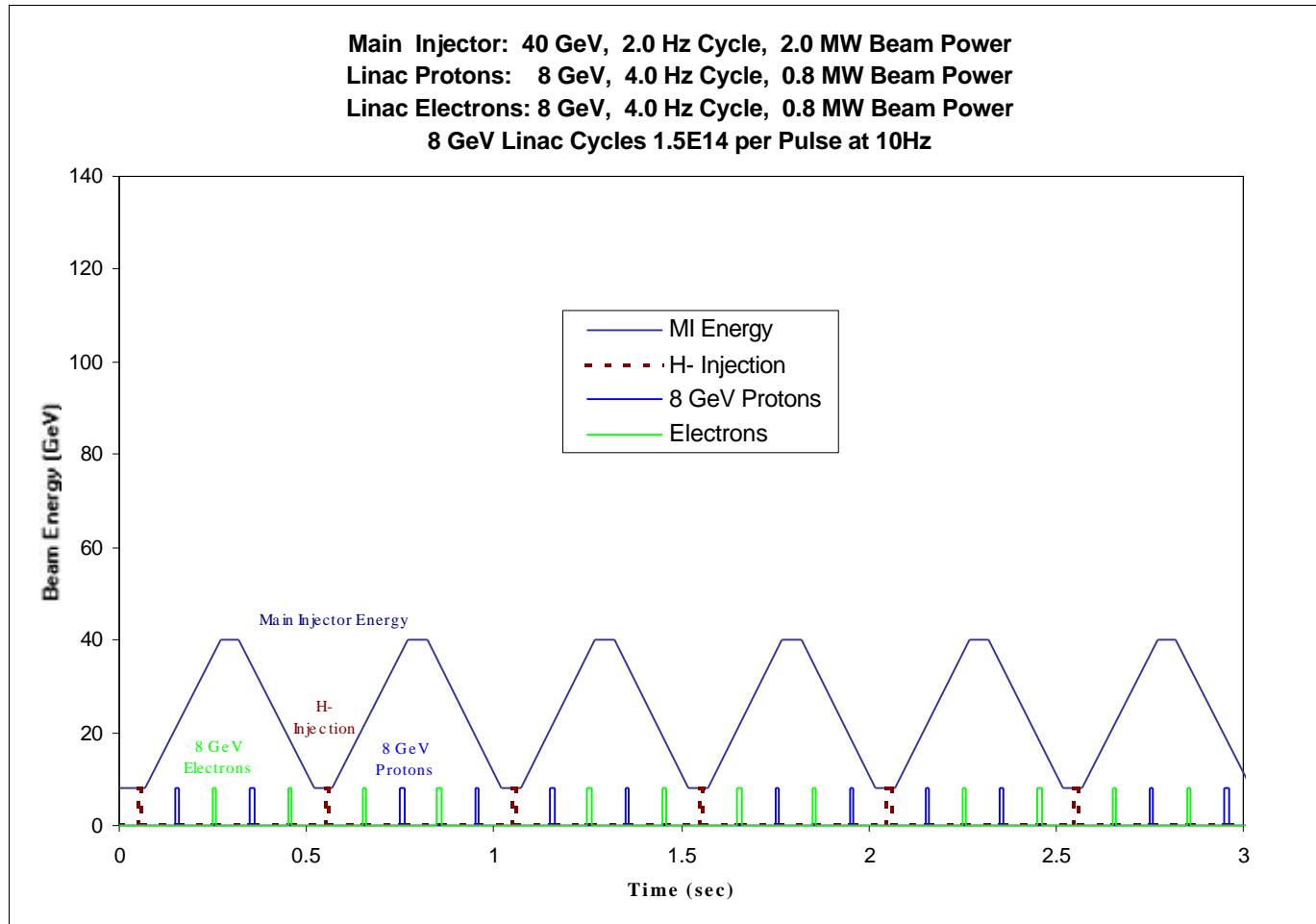
120 GeV Main Injector Cycle with 8 GeV Synchrotron



120 GeV Main Injector Cycle with 8 GeV Linac, e- and P

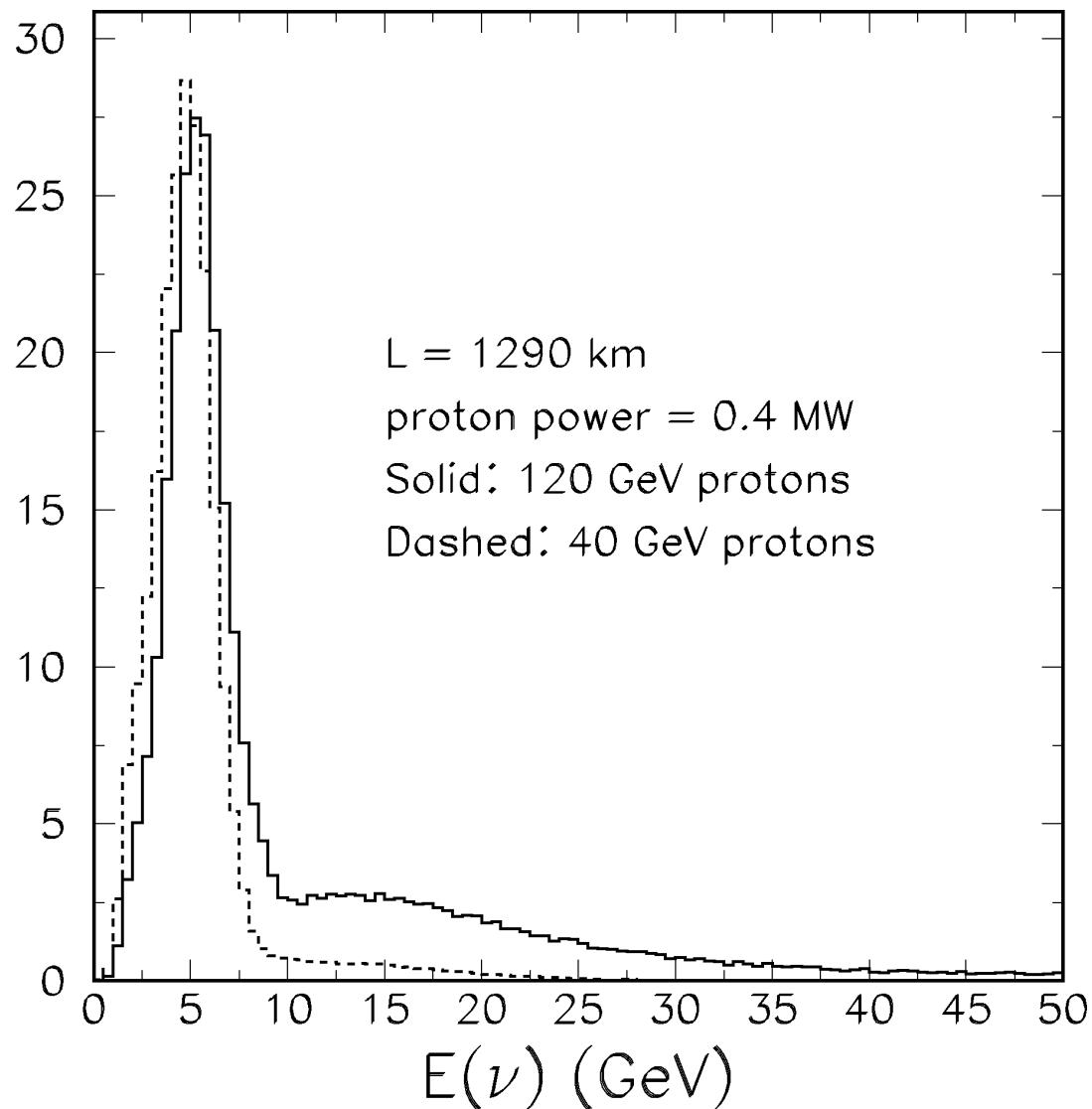
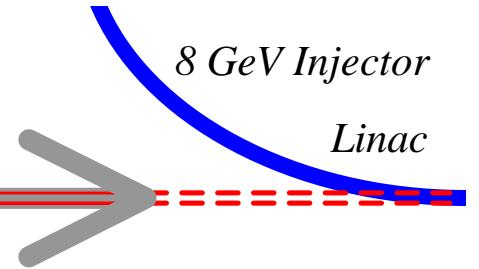


8 GeV Linac Allows Reduced MI Beam Energy without Compromising Beam Power



MI cycles to 40 GeV at 2Hz, retains 2 MW MI beam power

Running at Reduced Proton Energy Produces a Cleaner Neutrino Spectrum



Running at 40 GeV
reduces tail at
higher neutrino
energies.

Same number of
events for same
beam power.

(Plot courtesy Fritz & Debbie)

Cost Estimates



- 1) Scaled from TESLA costs
- 2) Scaled from SNS actual costs
- 3) Design Study Cost Estimate.
 - use SNS & actual costs where reasonable
 - independent, bottom-up cost estimates elsewhere
 - no unproven technology or speculative cost scaling

Rough Cost, Scaled from TESLA



- TESLA Project Cost (European) \$3B
- subtract damping rings, IR, Injector \$2.5B
- US Cost Basis (x2) for bare linac \$5B
- Scale to 7 GeV $(7/500) = 1.4\%$ \$70M
- TESLA Quantity Discount $(7/500)^{-0.074} = 1.37$ \$100M
- Include Fixed Project Cost (\$50M??) **\$150M**

Rough Cost, Scaled from SNS

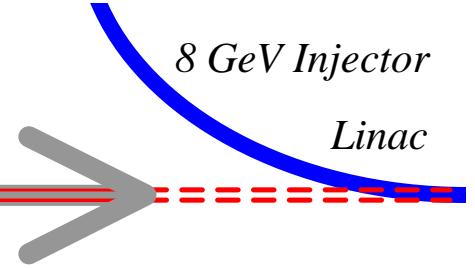


- SNS Project Cost \$1300M
- SC Linac Cost (approx, incl. civil) \$250M
- Scale SCRF by energy (7.6/0.8) x10
\$2.5 B

There are many good technical reasons why the TESLA linac should be cheaper. But how much?

Detailed breakdowns are needed to address the apparent disconnect between TESLA and SNS costs.

Cost Basis for 8 GeV Linac

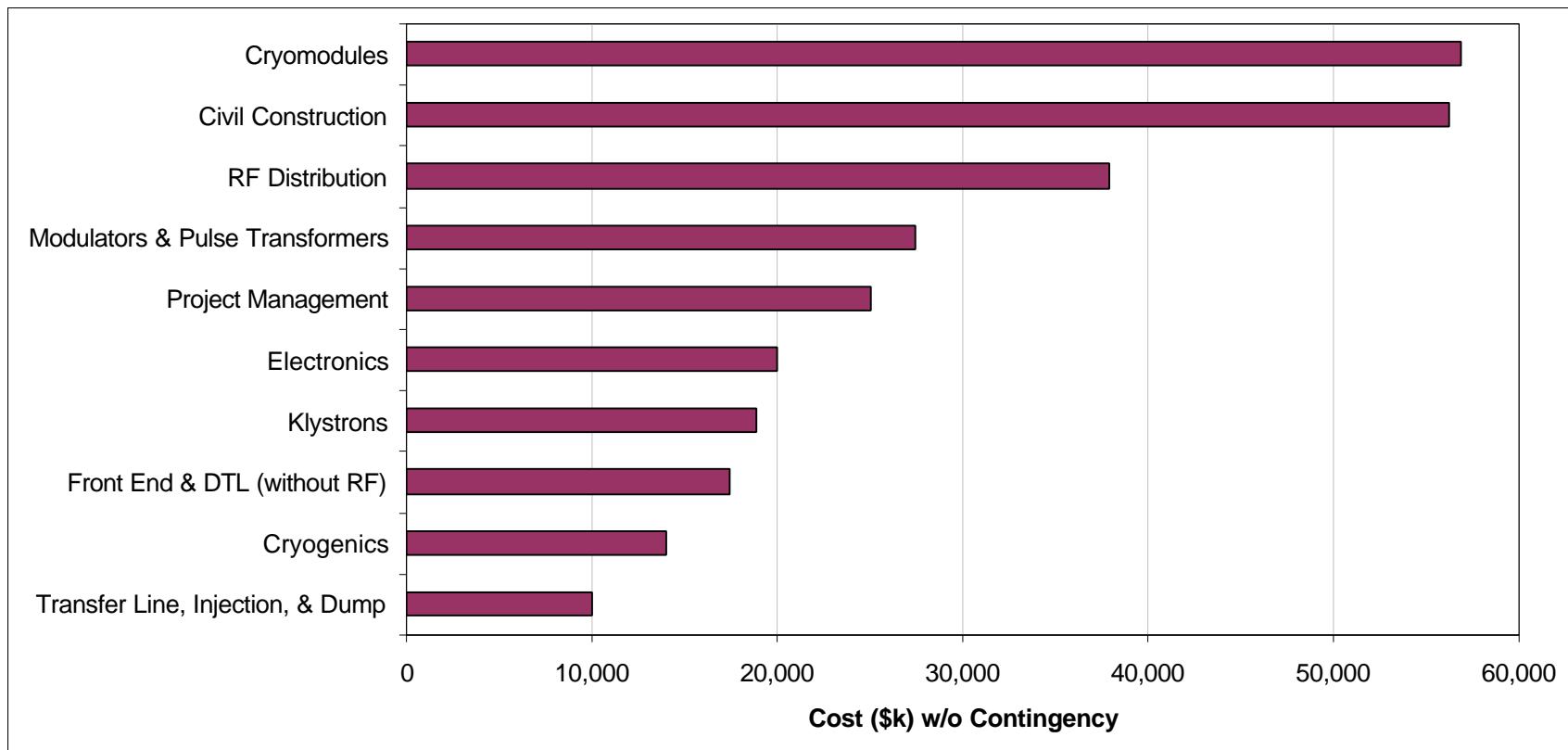


- SNS Actual Costs for:
 - Niobium & Finished Cavities (industrially produced)
 - Cavity tuners, RF Couplers, assembly labor, etc.
 - Klystrons, circulators, water loads etc.
- FNAL in-house cost estimates for:
 - TESLA-style Cryostat and Assembly Labor
 - TESLA-Style RF distrib. from U.S. vendor pricing
(much cheaper if offshore pricing used)
 - Cryogenics and Cryoplant (agrees w/SNS actuals)
 - Modulators based on FNAL-built units for TTF
 - Civil Construction, controls, & PM based on FMI

8 GeV Linac Cost Estimate



\$283M (x 1.3 Contingency) = \$369M



...so this is a Fermilab Main Injector sized project.

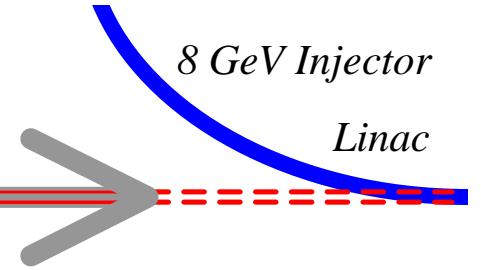
DISCLAIMER



- The cost estimate has not been reviewed
- Or exhaustively error-checked
- And may easily change 10-20% by time of final report
- But I believe it is OK.

Primary Parameter:

CHARGE PER PULSE



1.5 E14 protons (H-) per pulse

(same as SNS, approximately 2.5x TESLA)

... as specified by charge for Design Study.

Equivalent of ~ 35 FNAL Booster Batches / pulse

= 5x Main Injector design current

= 25 mA x 1 msec

Primary Parameter:

LINAC PULSE LENGTH



1 msec Beam Pulse ==> 25 mA Current

~ same pulse width as SNS and TESLA

- Many RF components & beam physics calculations (SNS) exist for this pulse width
- Conclusion of study is that 2.5 msec x 10mA might have been a better choice (==> fewer Klystrons)

(Technical questions for longer pulse include cavity resonance control, cryogenics, and H- injection)

Primary Parameters:

REP RATE & BEAM POWER



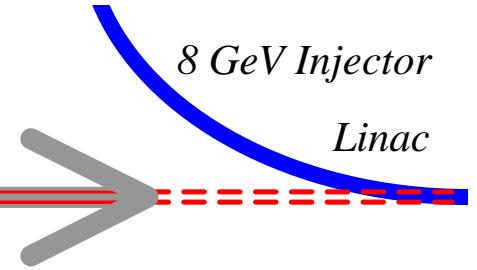
10 Hz Rep rate ==> 2 MW Beam Power

(TESLA XFEL: 10 Hz; SNS: 60 Hz)

- Only 0.7 Hz is necessary to fill Main Injector
- Existing 8 GeV experiment (BoonE) can only handle ~2Hz (400kW)
- Modest cost increase between 0.7 Hz and 10 Hz
- Reason for 10 Hz is for use w/ electrons &/or “SNS”
- Operating Wall Power = 2 MW standby + 1 MW/Hz

Primary Parameter:

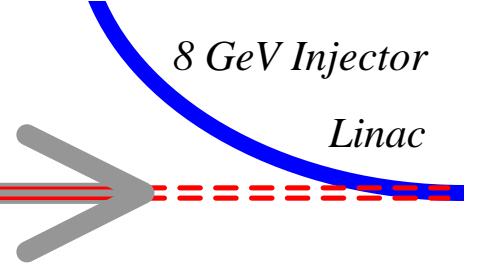
Acceleration of e-, H-, & P



Linac Specified to Accelerate H- and e- only

- 8 GeV Protons can be accumulated from H- in MI or Recycler, providing intense (10usec) beam spills
- Avoids pulsed (reversing) magnets in transport lines
- Interleaved e- running requires phase jump of cavities
 - Costs for fast ferrite Phase Shifters needed to run e- are \$4M-\$16M depending on detailed specifications
- Costs for XFEL lab considered to be “off budget”

Which Optimizations of SNS are worth it?



1) TESLA-style RF fanout

- drive many (8-12) cavities from single big klystron
- must complete SNS development of fast phase shifter

2) Eliminate warm Cavity-Coupled Linac (CCL)

- Use Beta=0.47, 805 MHz Superconducting cavities developed for RIA project by NSCL/Jlab/INFN
- Similar cryomodules & RF as Beta=0.61, 0.81 cavities
- SNS considered this but dropped due to schedule

3) Use TESLA-style cryomodules with cold quads

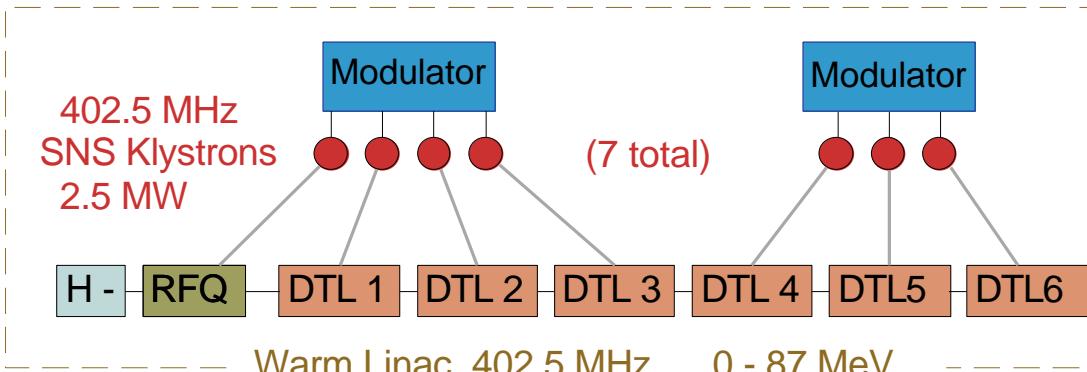
- longer cryomodules lower heat leak & fewer end costs

4) Civil construction for fewer klystrons per meter

Layout of 8 GeV Linac

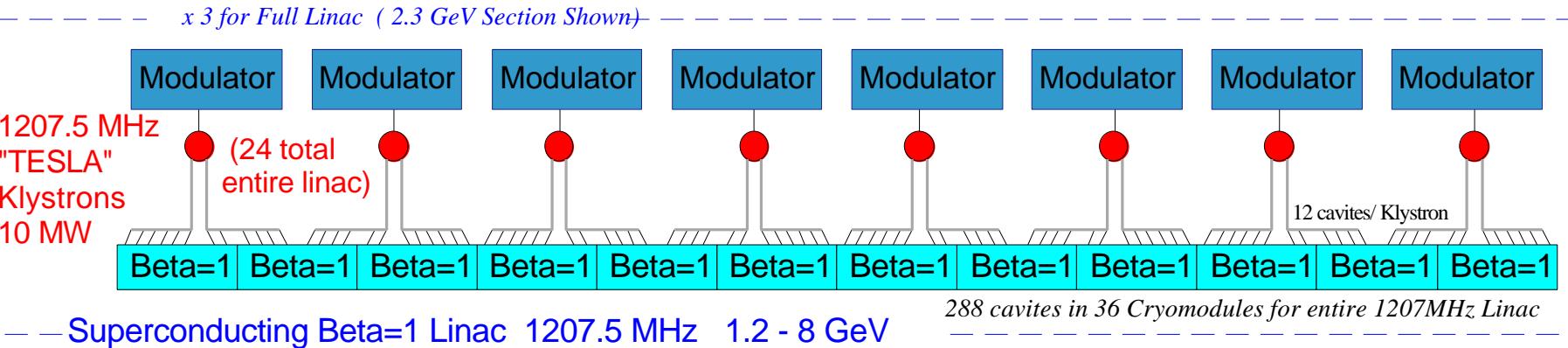
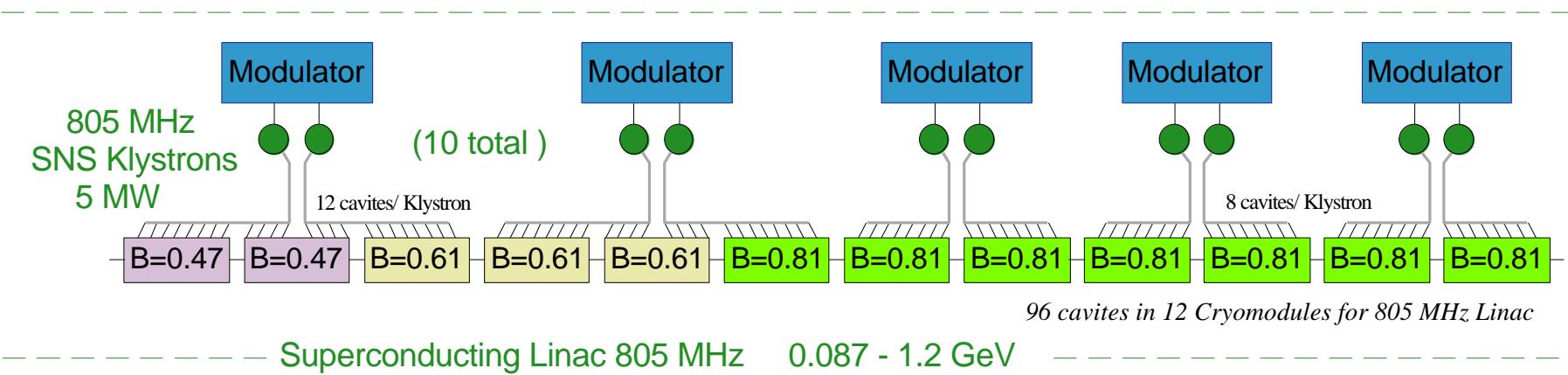


- Copy SNS 402.5 MHz RFQ & DTL up to 87MeV
- 805 MHz Superconducting Linac up to 1.2 GeV
 - Three sections: Beta = 0.47, 0.61, 0.81
 - Use cavity designs developed for SNS & RIA
 - TESLA-style cryomodules for higher packing factor
- 1.2 GHz “TESLA” cryomodules from 1.2-8 GeV
 - This section can accelerate electrons as well
 - RF from one Klystron fanned out to 12 cavites



8 GeV RF LAYOUT

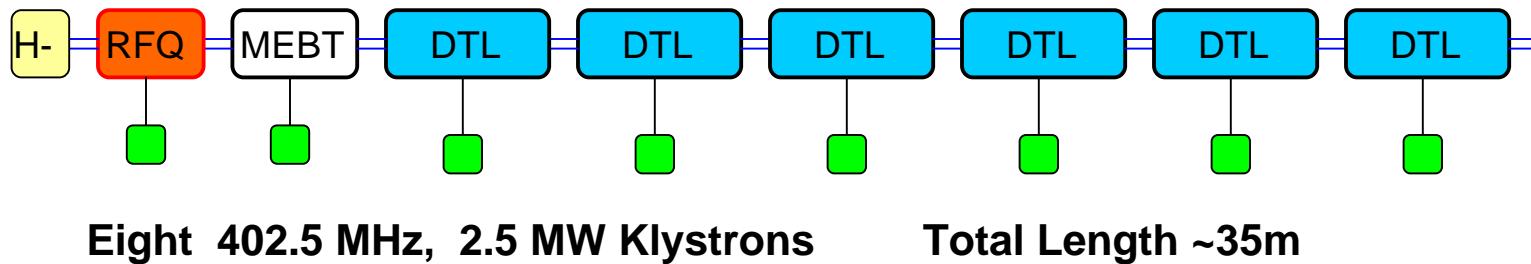
41 Klystrons (3 types)
31 Modulators 20 MW ea.
7 Warm Linac Loads
384 Superconducting Cavities
48 Cryomodules



Linac: 0 - 87 MeV



Copy of SNS Front End and Drift-Tube Linac (DTL) 0 ® 87 MeV



- Direct Copy of SNS Design:
 - H- Ion Source
 - RF Quadrupole (RFQ)
 - Simplified LEBT (buncher only)
 - Drift Tube Linac (402.5 MHz Normal Conducting)

SNS work provides technical existence proof

At Reduced RF Duty Cycle of ~1%,
the Front End is a Commercial Product

8 GeV Injector
Linac

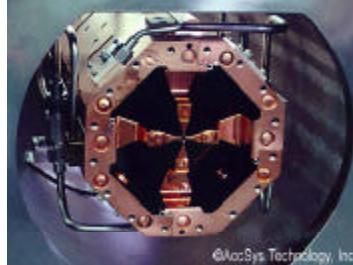


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CUSTOM LINAC SYSTEMS

AccSys' proprietary and patented linac technology can provide a wide range of ion beams and energies for specialized applications in research and industry. AccSys experts will design a system to customer specifications consisting of a carefully selected combination of our standard modular subsystems: radiofrequency quadrupole (RFQ) linacs, drift tube linacs (DTL), rf power systems and/or other components such as high energy beam transport (HEBT) systems and buncher cavities.

Radio Frequency Quadrupole Linacs



AccSys' patented Univane (US Patent No. 5,315,120) design provides a robust, cost-effective solution for low-velocity ion beams. This unique geometry incorporates four captured rf seals, is easy to machine, assemble and tune, and is inexpensive to fabricate. The extruded structure, which is available in lengths up to three meters, can accelerate ions injected at 20 to 50 keV up to 4 MeV per nucleon. Cooling passages in the structure permit operation at duty factors up to 25%.

Drift Tube Linacs



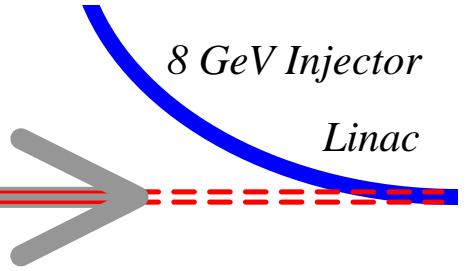
Drift Tube Linacs provide a cost-effective solution for ion beam energies above a few MeV per nucleon. Designed to accelerate ions from an RFQ, the DTL's permanent magnet focusing and high rf efficiency result in a minimum cost per MV. AccSys' patented drift tube mounting scheme (US Patent No. 5,179,350), which is integral to the twin-beam welded vacuum tank, provides excellent mechanical stability and low beam loss.

Commercially Available Front-End Linac (AccSys)

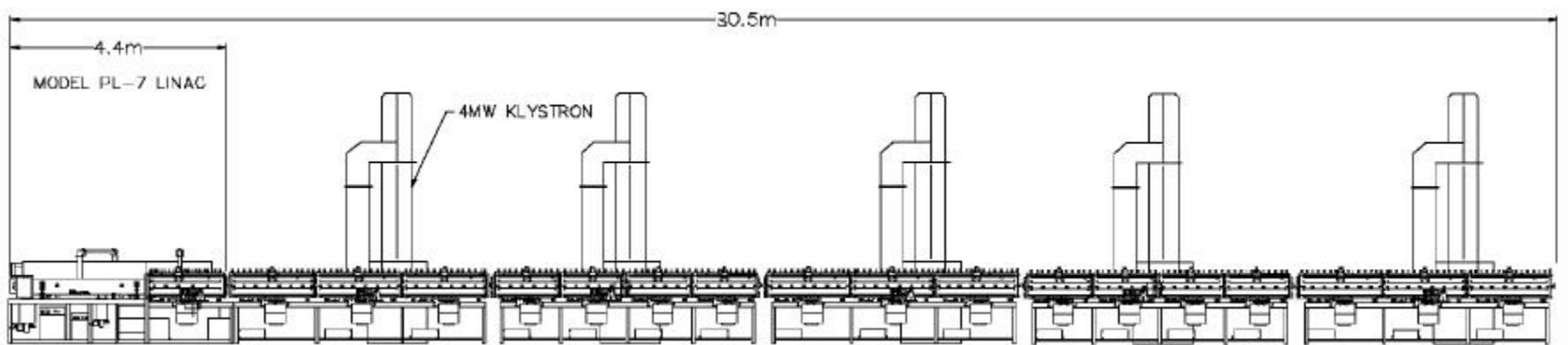


- Don Young has verified the applicability of the AccSys RFQ/DTL to various PD scenarios.
- This is a real product. Accsys has shipped multiple RFQ/DTL units for medical purposes in recent years. IUCF injector uses one.
- Vendor Estimate \$20M for turn-key operation @87MeV. (Less if FNAL provides the RF)
- This is very interesting for FNAL to pursue no matter what becomes of PD2 study.

AccSys Source/RFQ/DTL



- AccSys PL-7 RFQ with one DTL tank



- Appears to have shorter length and lower price than cloning the SNS Linac, *for 10 Hz operation*

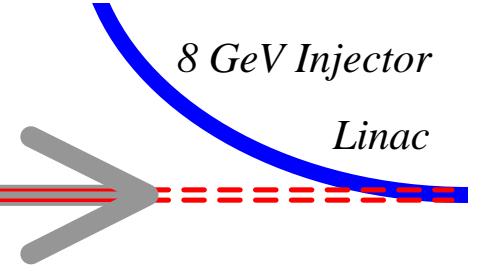
Transition from Copper to SC Linac



- Conventional Alvarez DTL is cost effective for $E < \sim 100$ MeV
- Above 100 MeV cavity-coupled linac (CCL) is best *copper* solution (e.g. FNAL linac upgrade)
- SNS chose CCL from 87-190 MeV, but recognized that money could be saved by using SC cavities in this energy range (no R&D Time)

The 8 GeV linac eliminates the CCL by using SC cavities (subsequently developed for RIA).

CRYOMODULES



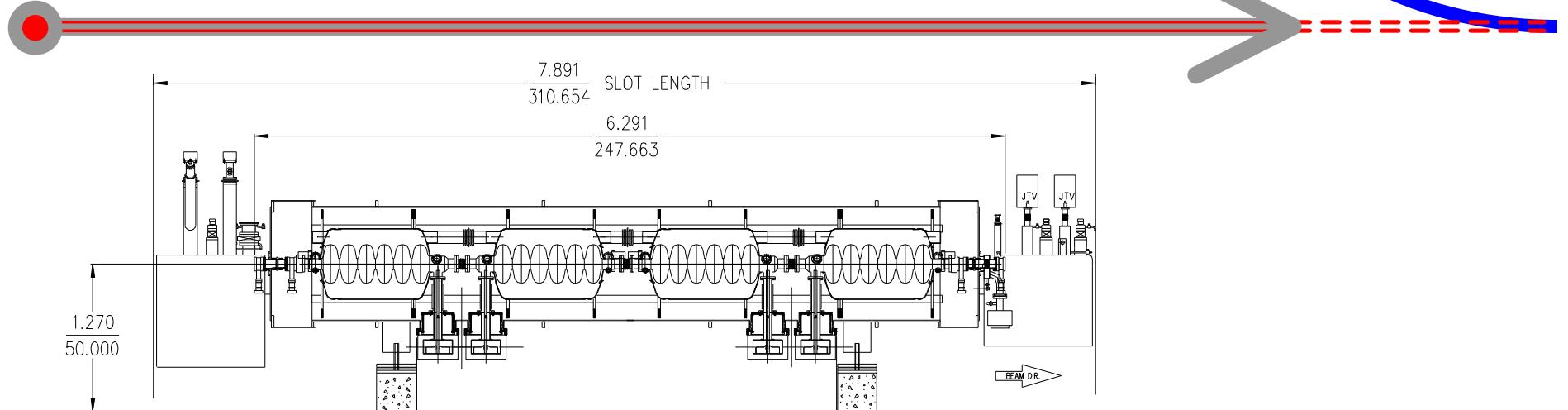
BIG Differences between SNS & TESLA

- Key Specification:
 - SNS Cryomodules can be swapped out in *~1 shift*
 - TESLA cryomodule replacement takes *~25 days* *
 - comes from having 2.5 km section of linac w/o bypass line
 - 8 GeV LINAC: *~2 day* repair time specified
 - possible because linac sector is much shorter ~300 m

(M. Geynisman)

* http://tesla.desy.de/new_pages/TESLA_Reports/2001/pdf_files/tesla2001-37.pdf

SNS/CEBAF Cryomodules

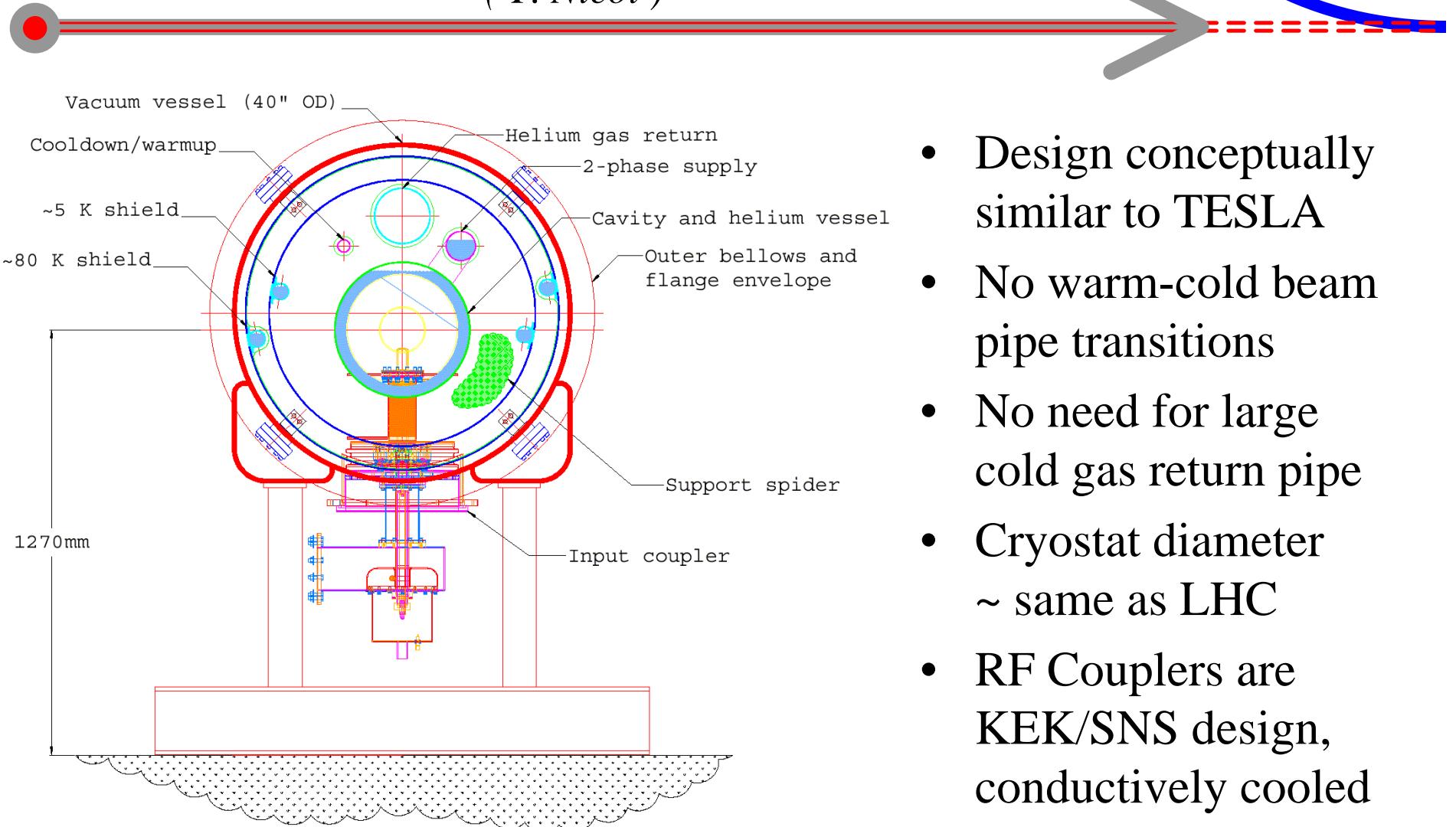


- Warm-to-cold beam pipe transition in each module
- 2K Coldbox, J-T & HTX in each Cryomodule
- Bayonet disconnects at each coldbox
- Only 2-4 cavities per cryomodule (f.f.~ 50%)

Expensive Design forced by fast-swap requirement

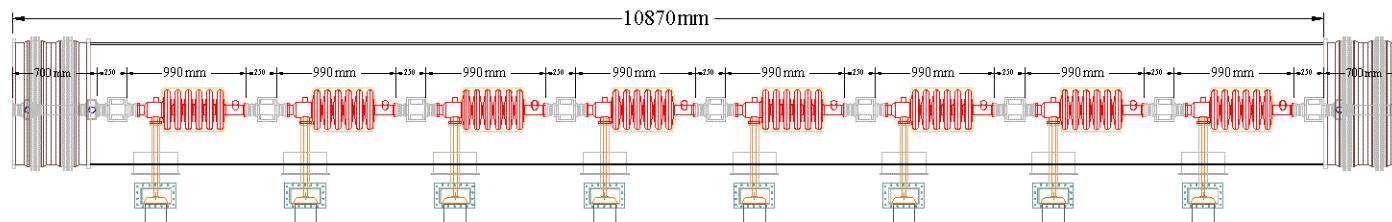
TESLA-Style Cryomodules for 8 GeV

(T. Nicol)



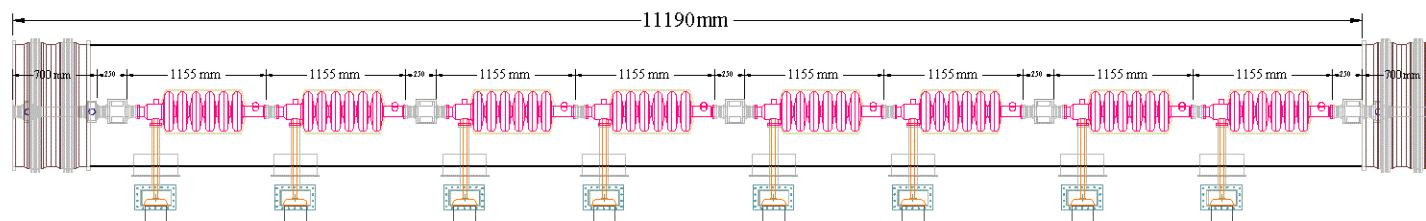
- Design conceptually similar to TESLA
- No warm-cold beam pipe transitions
- No need for large cold gas return pipe
- Cryostat diameter ~ same as LHC
- RF Couplers are KEK/SNS design, conductively cooled for 10 Hz.
(R. Rabehl)

8 GeV Linac Cryomodules - 4 Types



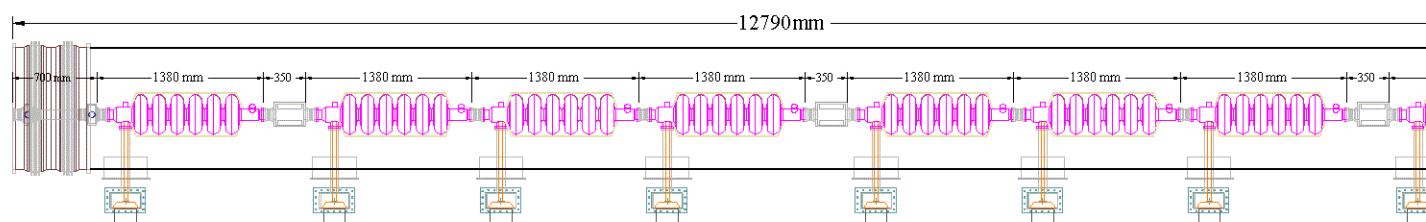
Beta= 0.47 (RIA)

87-175 MeV
2 Cryomodules
16 Cavities (RIA)



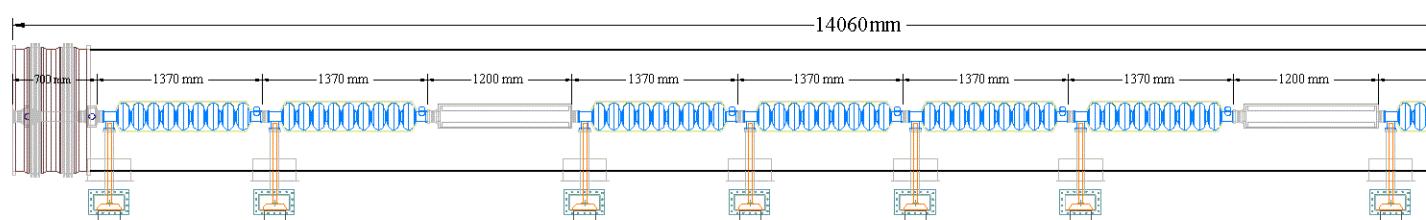
Beta= 0.61 (SNS)

175 - 400 MeV
3 Cryomodules
24 Cavities



Beta= 0.81 (SNS)

0.4 - 1.2 GeV
7 Cryomodules
56 Cavities

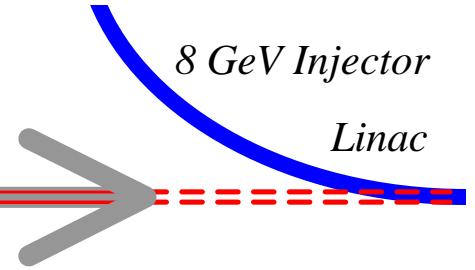


Beta= 1.00 ("TESLA")

1.2 - 8 GeV
36 Cryomodules
288 Cavities

9 Cell Beta=1 Cavities, 1207.5 MHz

Scaling of TESLA Cryomodules for 1-8 GeV



Frequency: 1300 MHz → 1207.5 MHz

- for compatibility with 805 MHz front-end Linac
- 1.2 GHz cavities must be ~ 8% larger than TESLA
- 8 Cavities per Cryomodule not 12 (TESLA)

Accelerating Gradient for Protons

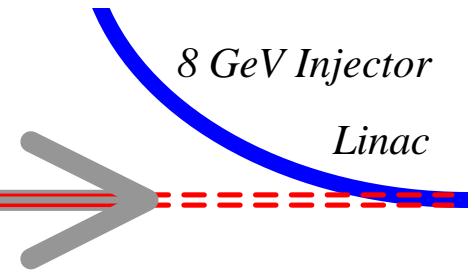
- Eacc ~ 23 MeV/m ($E_{peak} \sim 45 \text{ MV/m}$)
- Protons Linacs must run off-crest for phase stability ($\cos \sim 0.9$)

Number of Quadrupoles

- 8 GeV requires 2 quads per 16m cryomodule not 1/3
- Quads must be long ~1m to avoid H- stripping from B-field

Vacuum Breaks: every ~ 80m not 500m (design choice)

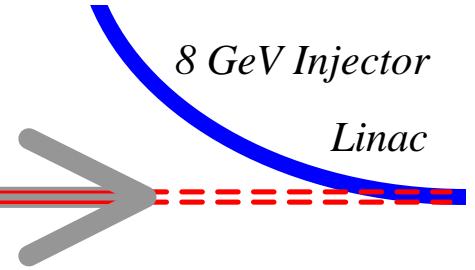
Cryomodule Technical Parameters



Number of Cryomodules	49	Linac + Debuncher modified by T Nicol for small GRP etc.			
Cryomodule Style	TESLA				
Warm-Cold Beam Pipe Transitions	No				
Bayonet Cryo Disconnects & cold box	No				
Quadrupole Type	Cold				runs at 2K
Cryostat Pipe Diameter (OD)	40 in.	1016 mm			
Cryostat Flange OD	46 in.	1168 mm			
Cryostat Material	Low Carbon Steel				de-Gaussed <i>in situ</i>
Magnetic field at cryomodules from rebar	< 0.005 Tesla				low-carbon steel cryostat provides shielding
Magnetic Shield Material around Cavities	cryoperm foil?				
Radiation Hardness	1.0E+08 Rads				
Cavity alignment tolerance WRT Cryomod	+/- 1 mm				TBD Maximum
Cavity tilt tolerance relative to cryomodule	+/- 1 mrad				TBD Maximum
Cryomodule transverse alignment tolerance	+/- 1 mm				TBD Maximum
Quad Alignment Tolerance WRT Cryomod	+/- 0.5 mm				TBD Maximum
Transportation Distance from Factory	2 km				FNAL IB2 to Front-End Bldg.
CRYOMODULE TYPES					
	LOW	MEDIUM	HIGH	"TESLA"	
Cryomodule Geometrical Beta of Cavities	0.47	0.61	0.81	1.00	
Number of Cryomodules in Linac	2	3	7	36	48
Spare Cryomodules	2	2	2	4	incl. debuncher
Length of Cryomodule slot for each Beta	10.870	11.190	12.790	14.060	
Number of Cavities Per Cryomodule	8	8	8	8	
Number of Quads Per Cryomodule	9	5	3	2	
Slot Lengths					
Cavity Slot Length incl. Bellows	0.990m	1.155m	1.380m	1.370m	
Quad Assy Slot Lengths	0.250 m	0.250 m	0.350 m	1.200 m	
Beam Profile Monitor Slot Length	0.200 m	0.200 m	0.200 m	0.200 m	1/cryomod
Cryostat Interconnect Length	0.500 m	0.500 m	0.500 m	0.500 m	TTF
Cold Mass					
Cold Mass of Quad/BPM Assy	12 kg	10 kg	12 kg	43 kg	see quad sect
Total 2K Cold Mass per Cryomodule	870 kg	895 kg	1023 kg	1125 kg	rough est.
Total 5K Cold Mass per Cryomodule	54 kg	56 kg	64 kg	70 kg	rough est.
Total 50K Cold Mass per Cryomodule	163 kg	168 kg	192 kg	211 kg	rough est.
Heat Loads					
2 K static heat load per Cryomodule	11 W	11 W	11 W	5 W	317 W
2 K total heat load per Cryomodule	20 W	20 W	20 W	14 W	775 W
6K Static Heat Load per Cryomod	35 W	35 W	35 W	14 W	951 W
6K Total Heat Load per Cryomod	43 W	43 W	43 W	23 W	1363 W
50K static heat load per Cryomodule	273 W	221 W	195 W	118 W	6956 W
50K total heat load per Cryomodule	312 W	260 W	234 W	235 W	11737 W
RF Coupler Type	-SNS	-SNS	-SNS	TTF	cond. cooled
Coupler LHe consumption / cryomodule	-	-	-	-	

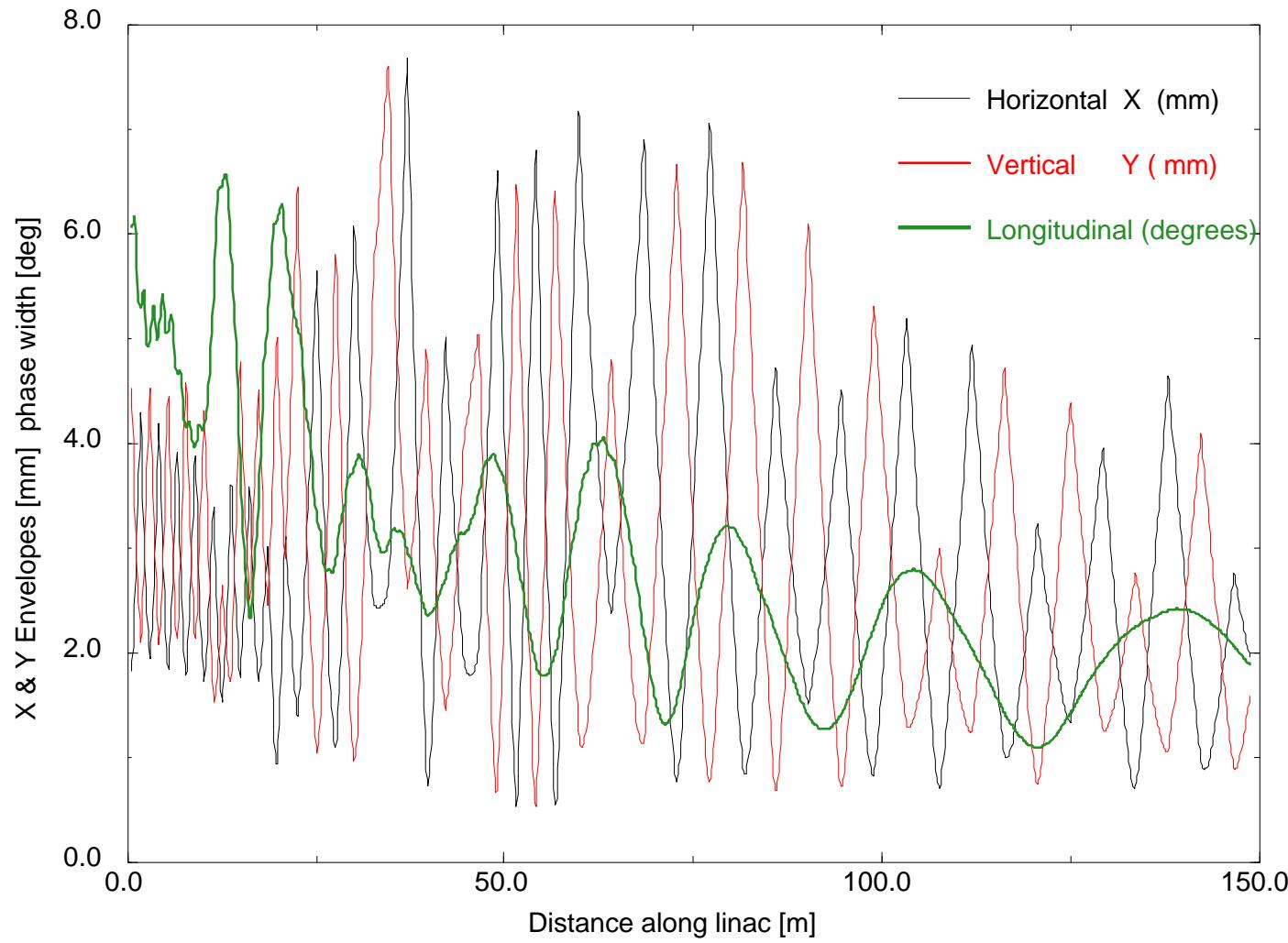
Self-Consistent Accelerator Physics Design

(Jim MacLachlan)



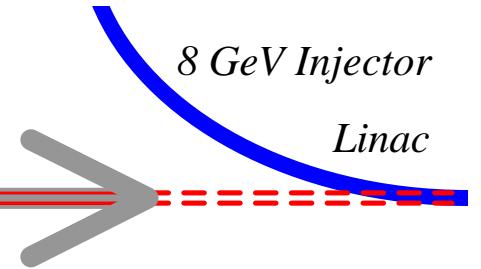
Beam Envelopes for the 8 GeV Linac

J. MacLachlan



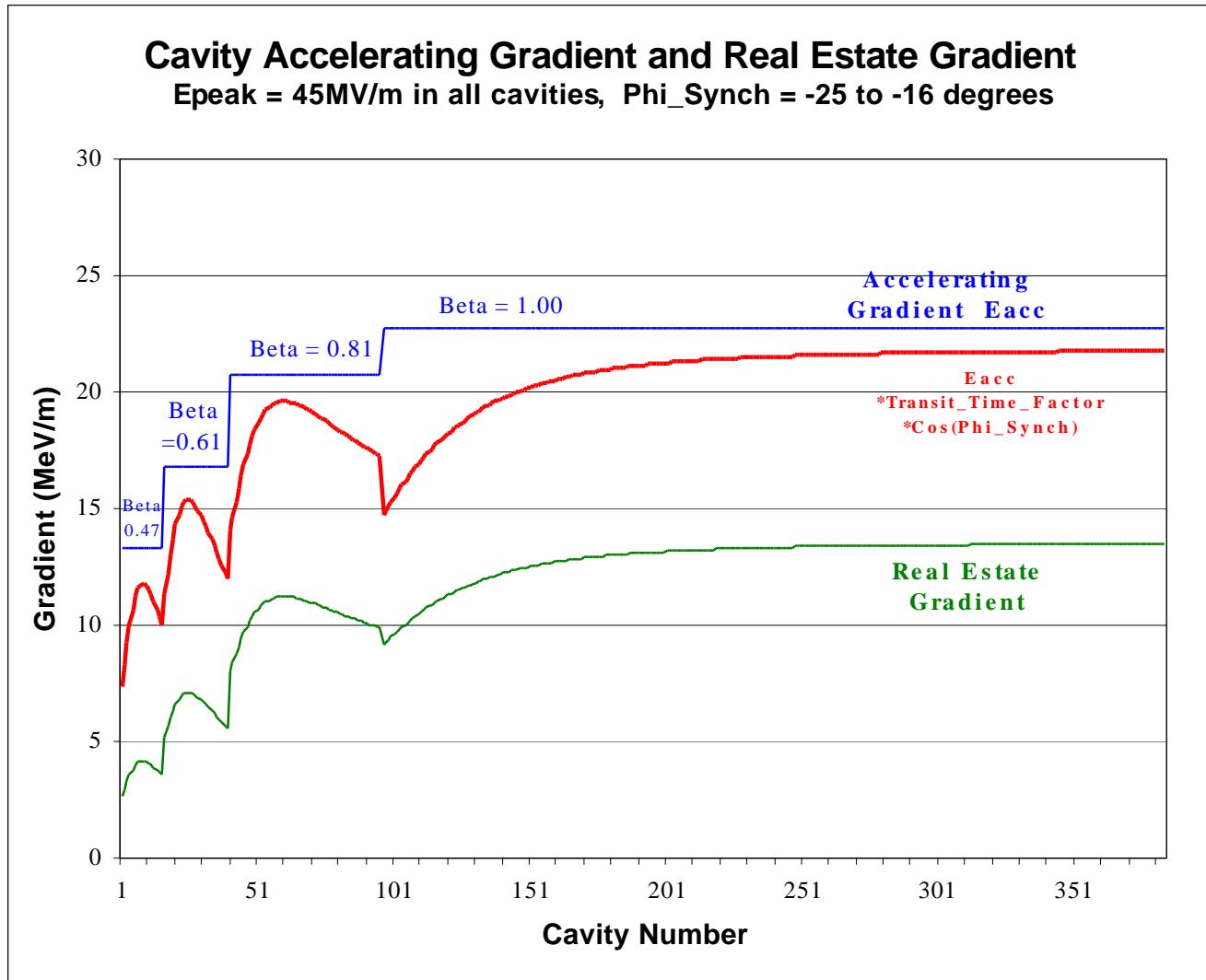
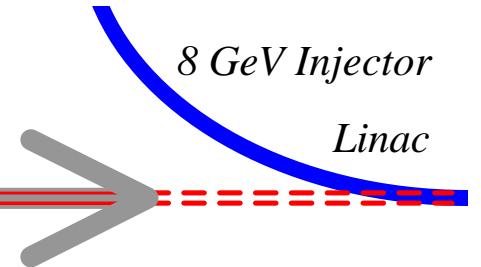
Had to increase number of quads to get to good design...

Quadrupole Technical Parameters



Number of Quadrupoles in Cryomodules	126 FODO not including transfer line or DTL			
Focusing structure	Cold Superferric Quads inside cryomodules (MSU/TRASCO)			
Quadrupole type	both H & V each quad			
Trim Dipole Windings Inside Quads	± 1 cm 1 uT 10 uT			
Trim Dipole Downstream Orbit Deflection	typical, varies along lattice during cavity cooldown after cavites are SC			
Stray Field at Cavites (quads unpowered)				
Stray Field at Cavites (quads powered)				
Cryomodule Type (Beta)				
Number of Quads Per Cryomodule	9	5	3	2
Number of Quadrupoles	18	15	21	72
Quad Slot Length	0.250 m	0.250 m	0.350 m	1.200 m
Quad Magnetic Length	0.150 m	0.150 m	0.250 m	1.100 m
Quad Integrated Strength (at max energy)	3.05 T	2.51 T	2.70 T	3.0 T
Quad Gradient at max energy	20.3 T/m	16.7 T/m	10.8 T/m	2.7 T/m
Quad Aperture Radius	40 mm	40 mm	40 mm	40 mm
Quad Pole Tip Field at max energy	0.81 T	0.67 T	0.43 T	0.11 T
H-minus Stripping Field at max energy	1.35 T	0.58 T	0.27 T	0.06 T
Beam Radius for Stripping (at max energy)	67 mm	35 mm	25 mm	22 mm
SRF Quadrupole Design Details				
Amps	25 A	25 A	25 A	25 A
Amp-Turns per pole	12,923	10,638	6,864	1,736
Turns/pole	517	426	275	69
Stored Energy (approx)	198 J	134 J	93 J	26 J
Inductance	0.6 H	0.4 H	0.3 H	0.1 H
SC Strand Diameter (including Insulation)	0.50 mm	0.50 mm	0.50 mm	0.50 mm
SC Coil Area (pole winding)	129 mm ²	106 mm ²	69 mm ²	17 mm ²
SC Coil Azimuthal Thickness	15 mm	15 mm	15 mm	15 mm
SC Coil Radial Thickness	9 mm	7 mm	5 mm	1 mm
SC Coil Inner Radius	45 mm	45 mm	45 mm	45 mm
Lamination Return Leg Thickness	16 mm	13 mm	10 mm	10 mm
Lamination Outer Radius	70 mm	65 mm	60 mm	56 mm
Approximate Weight	12 kg	10 kg	12 kg	43 kg

Superconducting Cavity Gradients



8 GeV design assumes *peak* field in cavities of 45 MV/m.

SNS:

37.5 MV/m

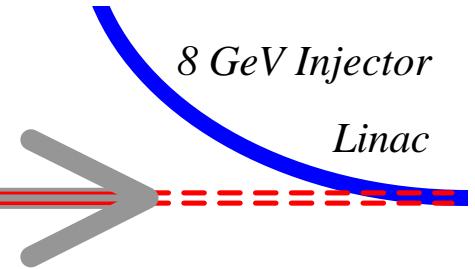
TESLA(500):

47 MV/m

TESLA(800):

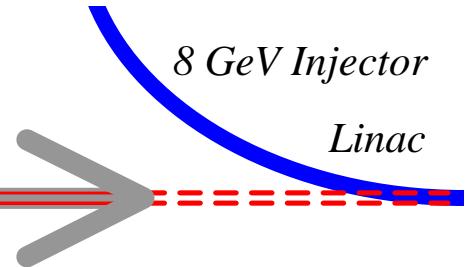
~70 MV/m

Cavity Technical Parameters



Number of Cavities in Linac	392	including 8 in debuncher cryomodule		
Cavity type	elliptical			
Cavity operating mode	pi			
Cavity material	Niobium			
Cavity material thickness	4 mm			
Cavity final processing	electropolish			
Cavity stiffeners	yes			
Allowed frequency swing due to Lorentz force	470 Hz			
Micromechanical amplitude limit	+/- 100 Hz	Six sigma		
Cavity operating temperature	~1.9 K			
Cryomodule Type (Beta)		LOW	MEDIUM	HIGH
Geometrical Beta of Sections		0.47	0.61	0.81
RF frequency (MHz)	805	805	805	1207.5
Cavity Type	RIA	SNS061	SNS081	"TESLA"
Number of Cells Per Cavity	6	6	6	9
Cell-to-Cell Coupling Constant	1.50%	1.61%	1.61%	1.87%
Unloaded Q ₀	>5E9	>5E9	>5E9	>1E10
External Q	7.5E+05	7.3E+05	7.0E+05	1.5E+06
External Q Variation	+/- 20%	+/- 20%	+/- 20%	+/- 20%
R/Q ₀ (function of beam velocity)	160	220-440	170-570	1036
Typical band width FWHM=f ₀ /(2Q _{ex})	537 Hz	551 Hz	575 Hz	403 Hz
Cavity Active Length (geometrical)	0.525 m	0.682 m	0.906 m	1.118 m
Cavity Total Length incl. Couplers	0.910 m	1.067 m	1.290 m	1.318 m
Cavity Slot Length incl. Bellows	0.990 m	1.155 m	1.380 m	1.370 m
Iris Diameter	77.2 mm	86.0 mm	97.6 mm	75 mm
ID at Equator	329 mm	329 mm	329 mm	223 mm
Epeak (max)	45	45	45	45
Epeak/Eacc	3.41	2.71	2.19	2.0
Eacc (max, on crest for Beta-design)	13.2	16.6	20.5	22.5
Bpeak/Eacc	6.92	5.73	4.79	4.26
Bpeak	91.3	95.1	98.4	95.9
Synchronous Phase Phi (typ)	-25	-22	-19	-16
Eacc*Cos(Phi)	12.0	15.4	19.4	21.6
Energy Gain Per Cavity (max)	6.3	10.5	17.6	24.2
Coupler Power (max) for 25mA Beam	157	262	440	605

SNS Cavity Fabrication



Deep drawing & machining



Dumb-bells



Frequency adjust



Welding



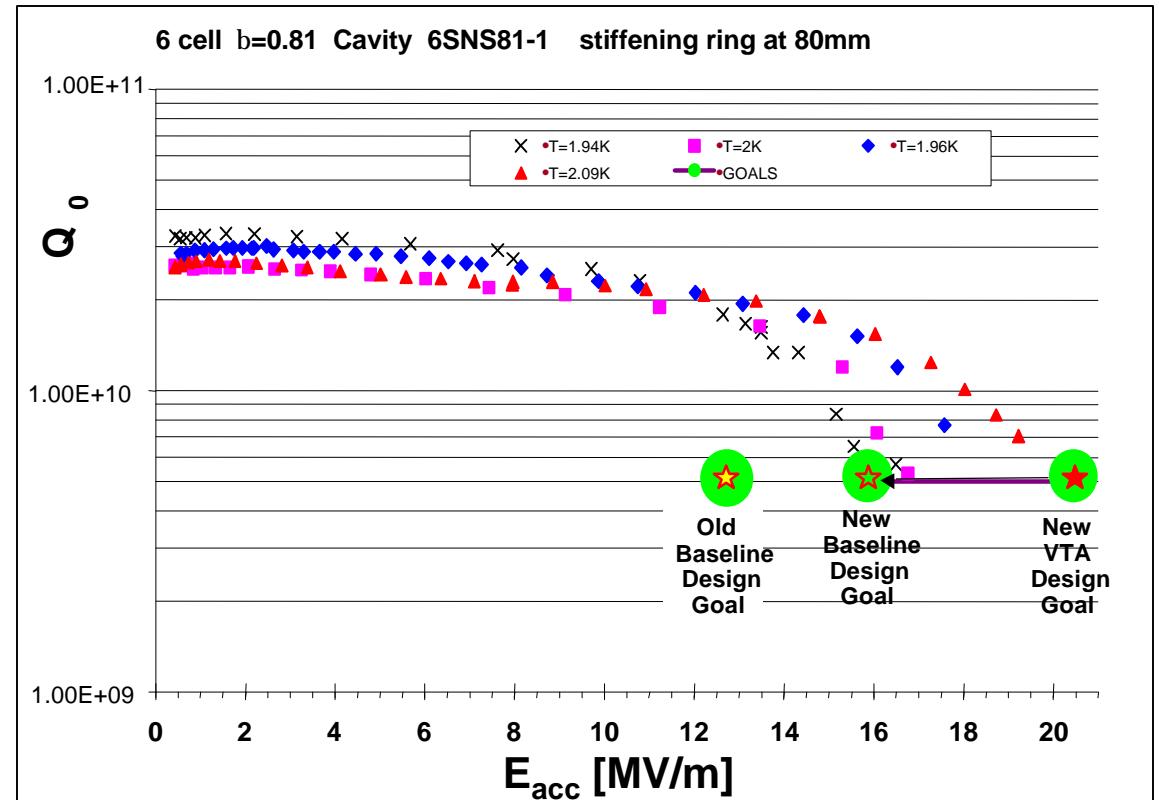
SNS $\beta=0.61$



Tuning



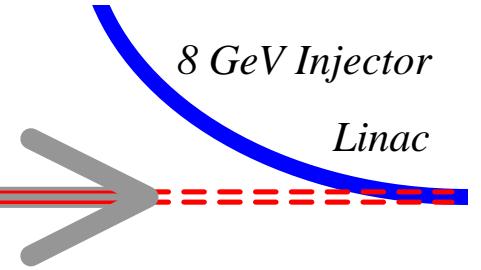
SNS $\beta = 0.81$ Tests at TJNAF



[from N. Holtkamp Nov '01 SNS Review]

**$E_{acc} > 20 \text{ MV/m}$ for protons
is now reasonable design goal**

SNS Cavity Costs



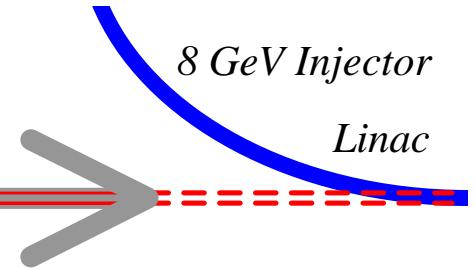
- We have graciously been given access to SNS actual costs for ~110 completed SCRF RF cavities, tanks, tuners, couplers, etc. including final chemistry and assembly labor.
(Thanks to N. Holtkamp, E. Daly, Katherine Wilson)
- The 8 GeV Linac needs 416 cavity assemblies
⇒ **\$35M for 8 GeV Linac**
- This assumes:
 - no quantity discount or rebate for existing tooling
 - that 1.2 GHz 9-cell cavities are the same price as 805 MHz 6-cell SNS cavities of same length

8 GeV Cryomodule Costs



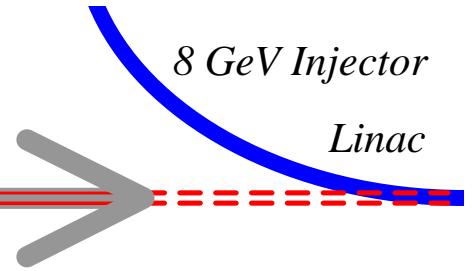
- Costs for SNS cavity assemblies and RF power couplers integrated into TESLA-style cryomodules were estimated by T. Nicol (TD)
 - Tom is the project manager for US LHC cryostats
 - USLHC requires ~270m of cryostats, 8 GeV ~ 650m
- Final Cost including cavities, cryostats, RF couplers, EDIA & labor, no contingency:
 - 52 Cryomodules @ \$1093k ea. = \$57M
... this is the biggest single cost component

Cryomodule Cost Estimate



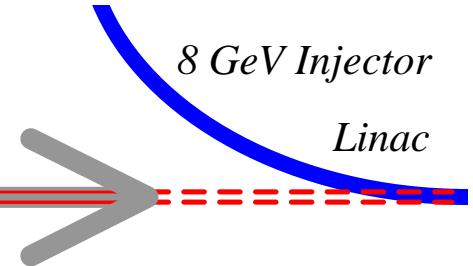
ITEM	Unit	M&S Cost	Quantity	M&S Tot.	Eng/Mgr	Tech	Phys	Labor	Total
		\$		\$k	FTE-yr	FTE-yr	FTE-yr	\$k	\$k
Cryomodules									
Cryomod.Unit Cost Rollup w/o Quads	C.M.	\$966k/CM	52	52,634	14	33	10.6	4,220	56,854
Cavity Assemblies	ea	72,000	8 /CM	\$576k/CM	5	5	5	1,100	1,676
Cavity incl. Nb and HOM couplers	ea	40,000	8 /CM	\$320k/CM					320
Cavity Final Chemistry & Prep	ea		8 /CM	\$0k/CM					
Helium vessel	ea	10,000	8 /CM	\$80k/CM					80
Tuners	ea	11,000	8 /CM	\$88k/CM	1	1	1	220	308
Motor	ea	2,200	8 /CM	\$18k/CM					18
Harmonic Drive	ea	1,000	8 /CM	\$8k/CM					8
Frame	ea	6,000	8 /CM	\$48k/CM					48
Piezo Tuners	ea	1,800	8 /CM	\$14k/CM					14
RF Power Coupler	ea	30,000	8 /CM	\$240k/CM	2	7	1	740	980
Vacuum vessel components & Assy	ea	30,880	1 /CM	\$31k/CM	2	12		1,040	1,071
Vacuum vessel	ea	30,880	1 /CM	\$31k/CM					31
MLI (all)	ea	6,730	1 /CM	\$7k/CM					7
50K to 70K shield	ea	7,865	1 /CM	\$8k/CM					8
5K shield	ea	7,865	1 /CM	\$8k/CM					8
Support	ea	5,500	8 /CM	\$44k/CM					44
Invar tie bars	ea	1,650	14 /CM	\$23k/CM					23
Gas return pipe	ea	1,000	1 /CM	\$1k/CM					1
2K two-phase supply	ea	500	1 /CM	\$1k/CM					1
Cooldown/warmup line	ea	500	1 /CM	\$1k/CM					1
Piping supports	ea	350	8 /CM	\$3k/CM					3
Helium vessel attach brackets	ea	580	16 /CM	\$9k/CM					9
Magnetic shields	ea	10,000	2 /CM	\$20k/CM					20
Interconnect parts	ea	27	1 /CM	\$27k/CM	1	2		280	307
Instrumentation Inside Cryomodules	lot	5,000	1 /CM	\$5k/CM	1	2	1	280	285

CRYOGENICS & CRYO PLANT



- 8 GeV Linac Cryoplant is ~ same size as SNS
 - Linac is longer: 8 GeV vs. 1 GeV
 - RF Duty Cycle is smaller 1% vs. 6%
 - *Dynamic heat load is about the same*
- 8 GeV Linac Static heat leak per meter is similar to TESLA (TTF)
 - No bayonet or cold box heat loads per cryomodule
 - *Standby heat load < ~ SNS*

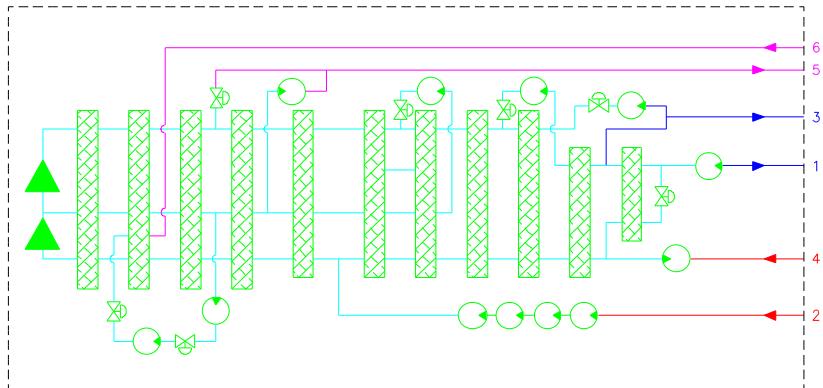
CRYOGENICS & CRYO PLANT



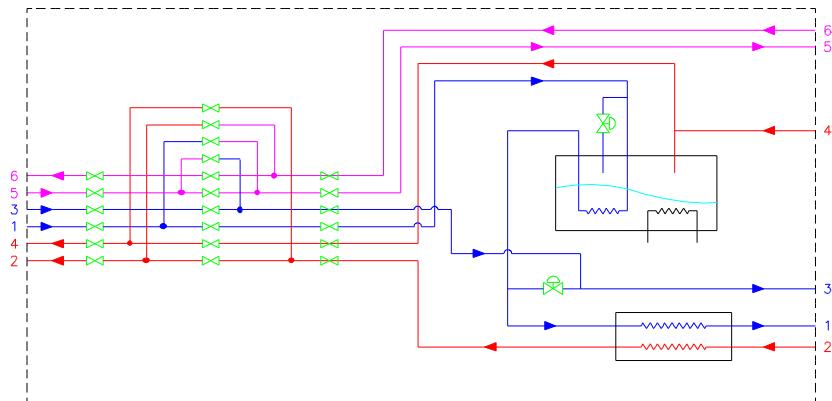
- Arkadiy Klebaner (BD) is doing detailed analysis of 8 GeV linac cryogenic requirements & cost
- Tom Nicol(TD): cryostat detailed design & costs
- Tom Peterson (TD): System Heat Loads
- Michael Geynesman (BD): cool-down calcs.
- Roger Rabehl (TD): power Coupler calcs

These guys are the top draft choices and really they know what they are doing.

Cryoplant and Distribution Box

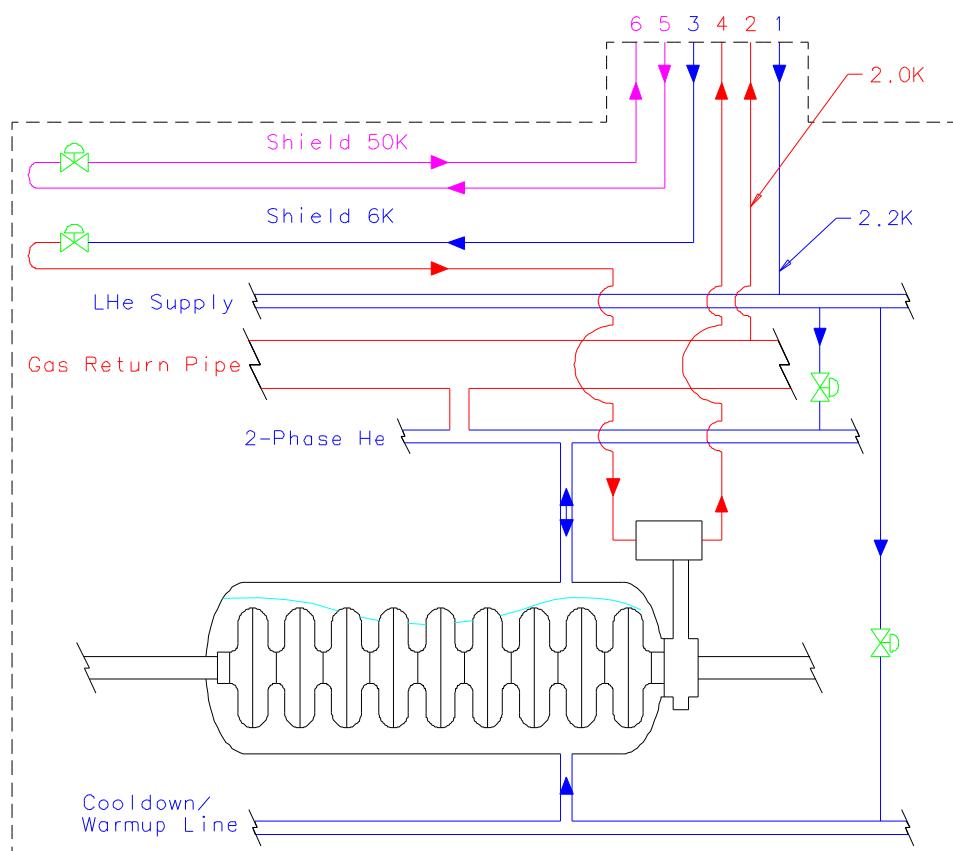
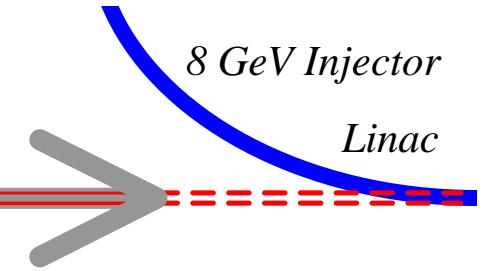


Cryoplant Process Flow



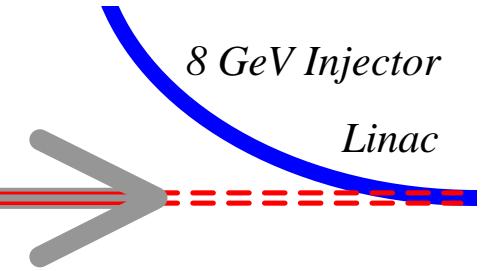
Distribution Box
and Transfer Line
Flow Schematic

Cryomodule Coolant Flows needed for 48-hour Module Replacement



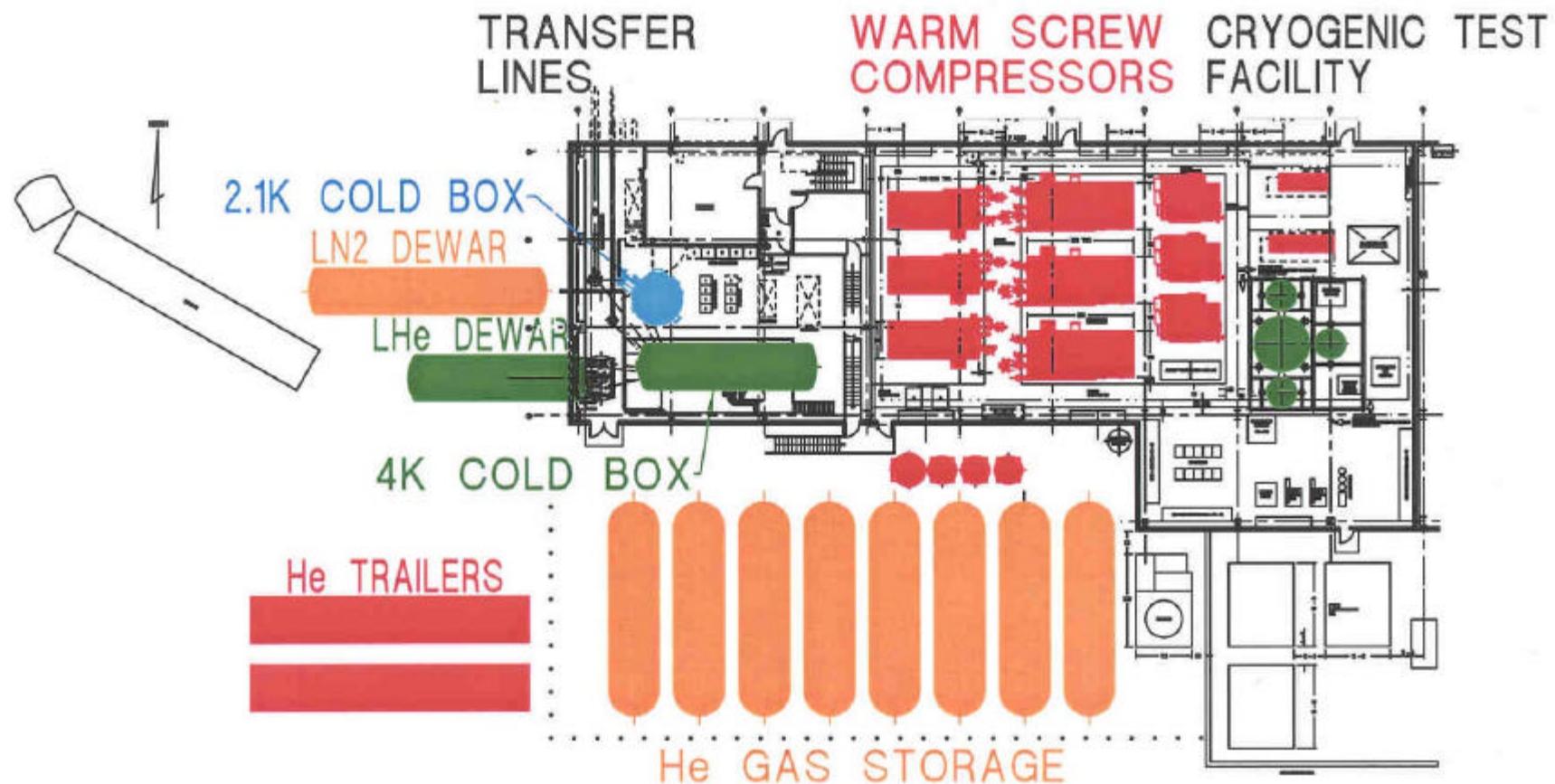
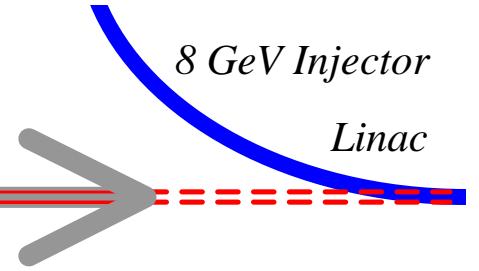
- It appears we can meet the 48-hour target using LN₂/GHe precooling and warm-up heaters
- Thermal stresses may be an issue

Cryogenic Technical Parameters



Nominal Refrigeration Power	9.8 kW of 4.2K Equiv Refrigeration		
Nominal Compressor Wall Power	0.73 MW	at 10 Hz operation	
Standby Compressor Power	0.38 MW	nominal static heat load only	
Installed Compressor Power	1.43 MW	includes overcapacity for cool down, etc.	
Electrical Service Required @Cryoplant	3 MW		
Number of Indep. Cryogenic Segments	2+1	Upstream & downstream, +Test Stand	
Cryomodule Replacement Time	48 hrs	Target	
Warm-up or Cool Down time	18 hrs	Prelim. Est.	
Distance between Vacuum Breaks	50 m	TBD	
Inventory Control			
Helium Inventory	1800 kg He	100%	rough est.
Liquid Storage	2500 kg He	139%	one 20,000 gal LHe dewar
Gas Storage	2000 kg He	111%	eight 30,000 gal gas tanks
Warm Gas Return Header for Cooldown	900 m		6" IPS SS pipe in tunnel
Cryogenic Transfer Lines			
Cryoplant to Linac	60 m		
Linac to Debuncher	180 m		
Cryomodule Test Stand	20 m		
CRYO FLOWS			
Temperature Out [K]	2.1 K	8.0 K	59 K
Temperature In [K]	2.2 K	6.0 K	50 K
Pressure Out [Pa]	4.1 kPa	500 kPa	1400 kPa
Pressure In [Pa]	110 kPa	550 kPa	1600 kPa
Predicted Static Heat Load [W]	326	1,081	8,216
Predicted Operating Heat Load [W]	780	1,476	12,881
Heat Uncertainty Factor [-]	1.3	1.3	1.3
Overcapacity Factor [-]	1.5	1.5	1.5
Design Heat Load [W]	1,521	2,879	25,118
Design Mass Flow [kg/sec]	0.07	0.126	0.532
Design Ideal Power [kW]	135	126	159
Nominal Operating Power [kW]	480	141	112
Nominal Standby Power [kW]	201	104	72
Installed Operating Power [kW]	936	276	219
			734 kW
			376 kW
			1431 kW

SNS CHL Facility



8 GeV Linac Cryoplant will be comparable ~\$15M

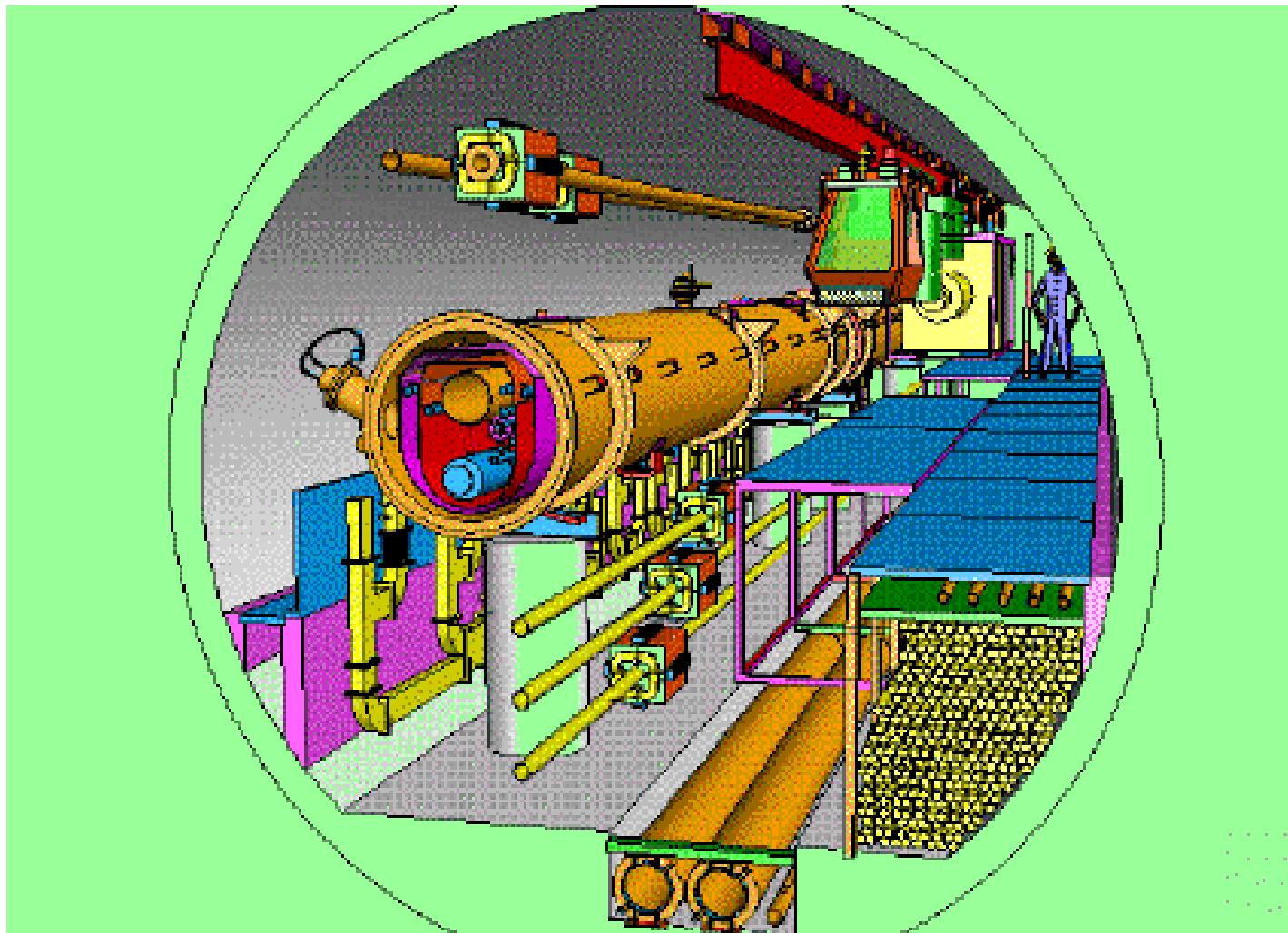
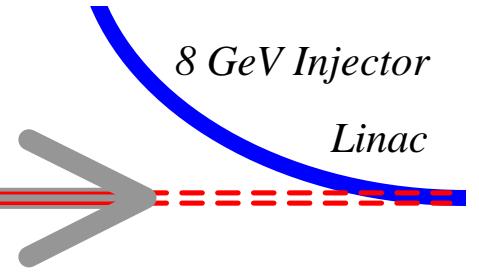
RF System for 1 → 8 GeV Linac



- Must assume TESLA-style RF distribution works
This will require fast phase shifters for individual cavity control
- One TESLA multi-beam Klystron per ~12 Cavites
 - 24 Klystrons 10 MW each
 - 288 total 1207 MHz power couplers 600kW each
- Modulators are identical to TESLA modulators
- Rough Cost: \$1.5M / RF station \Rightarrow \$45M
(TESLA costs & scaling rule* gives \sim \$31M)

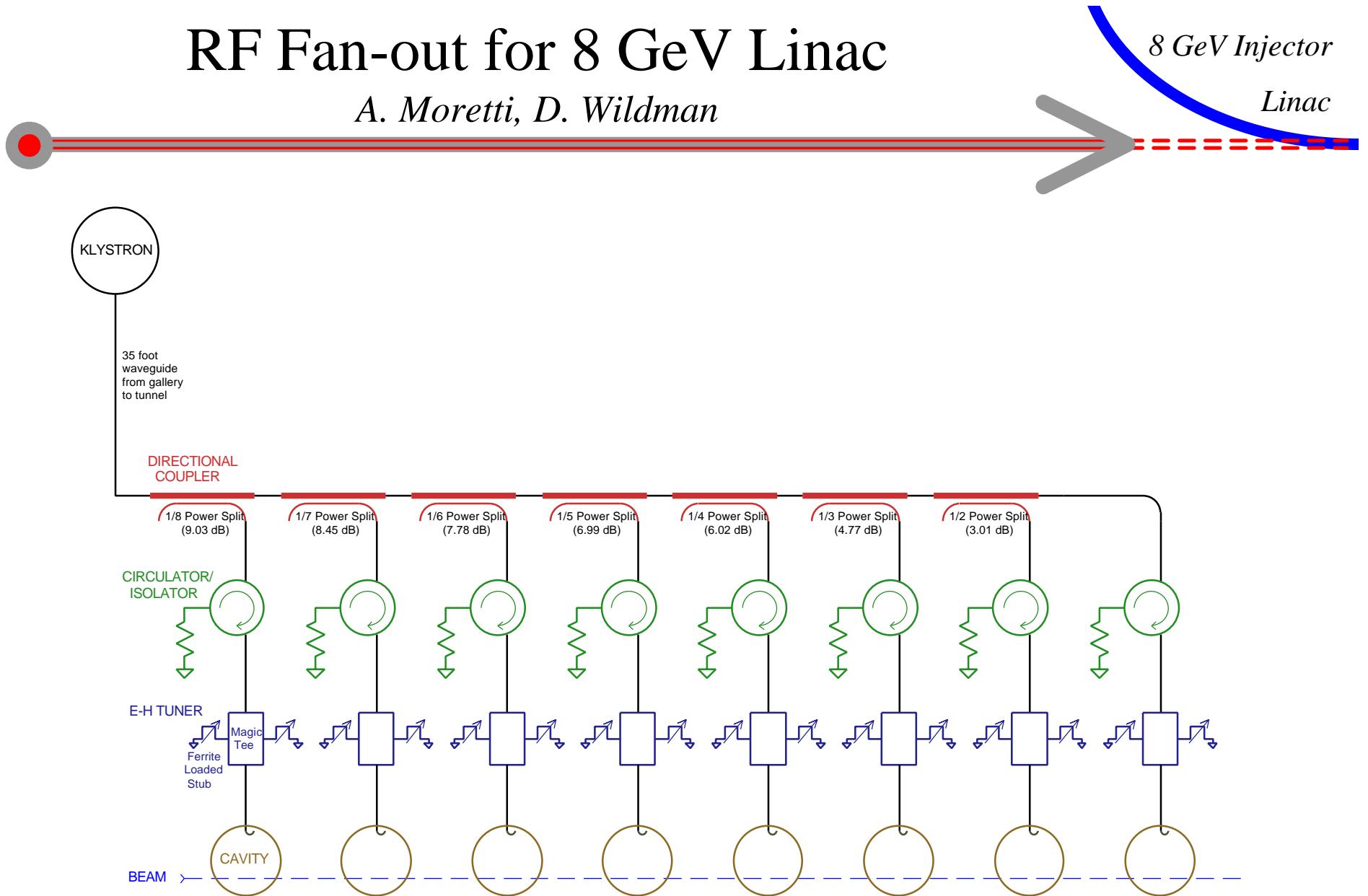
*cost proportional to (quantity) $^{-0.074}$

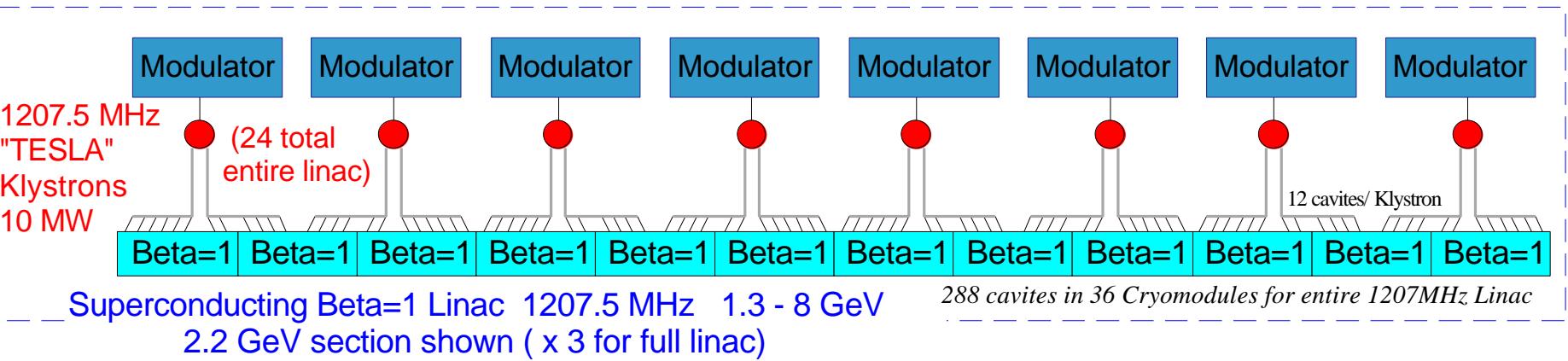
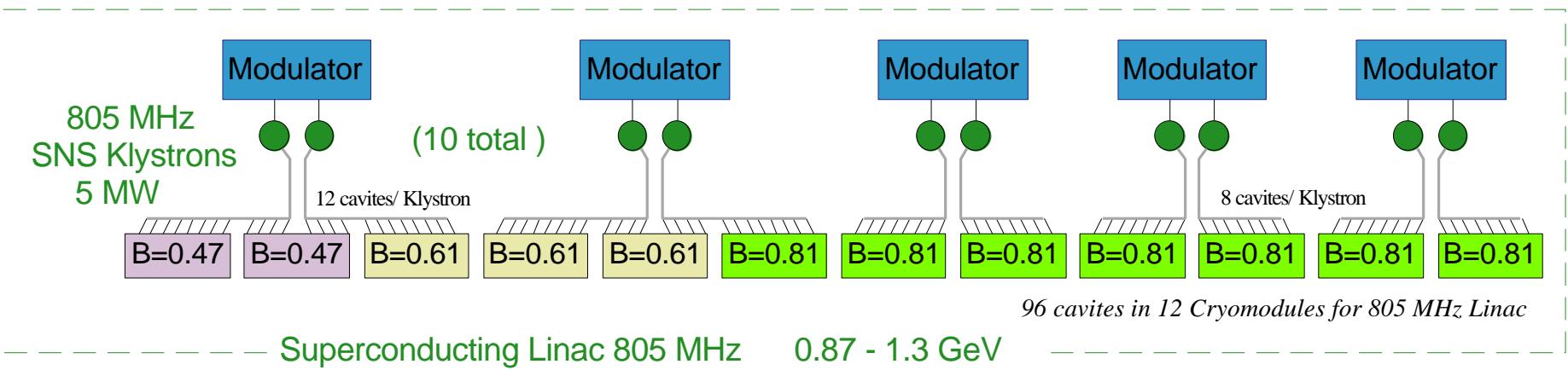
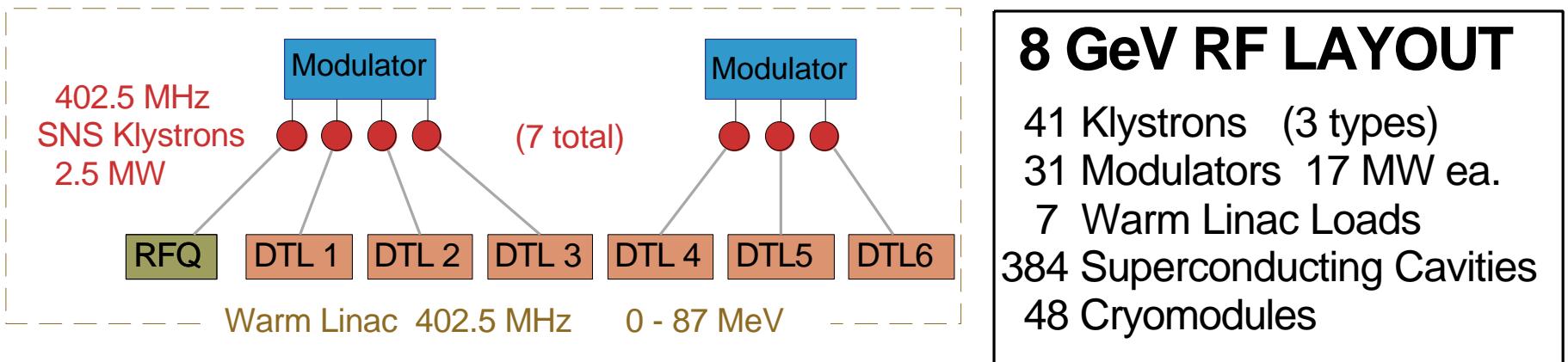
TESLA Tunnel & Klystrons



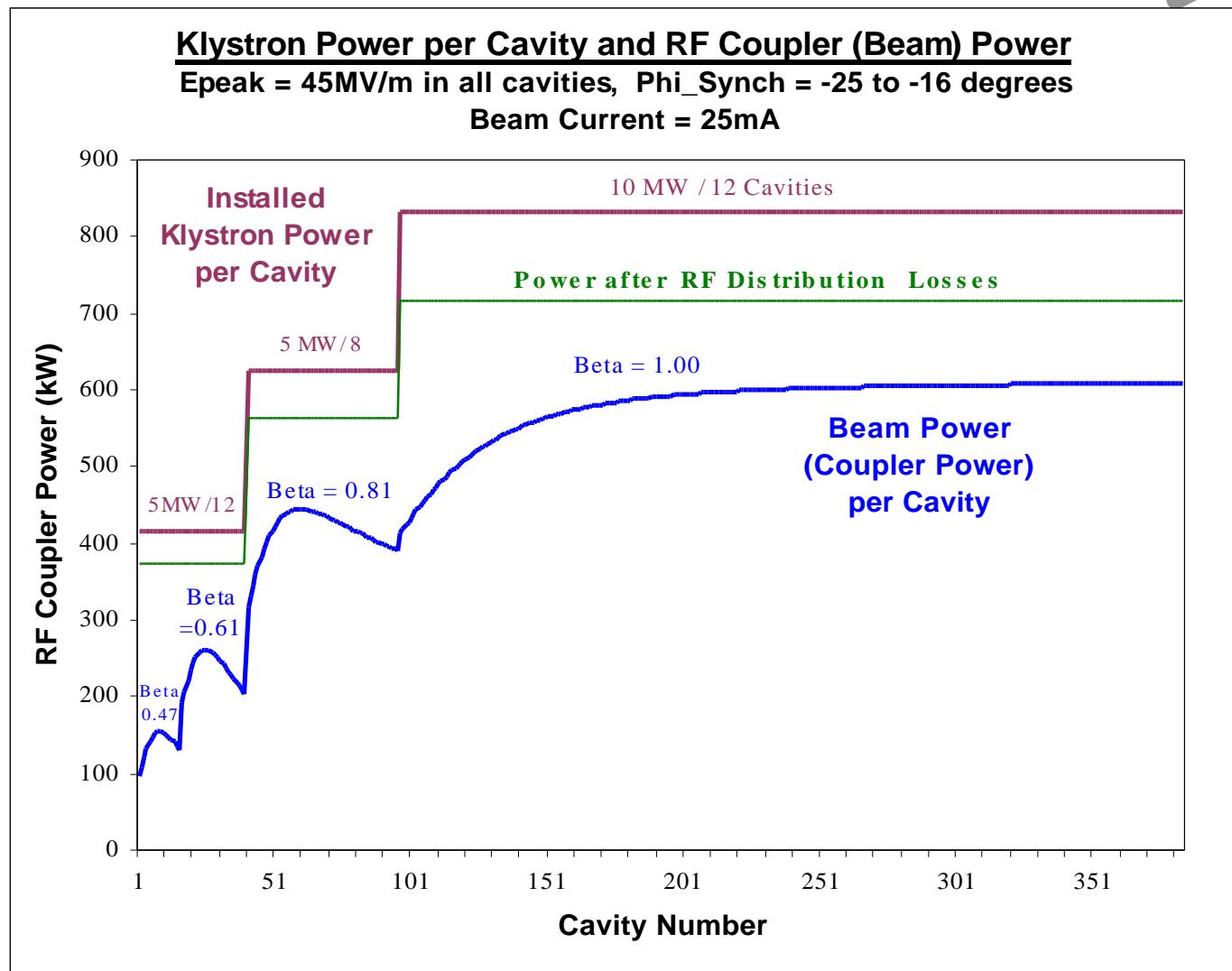
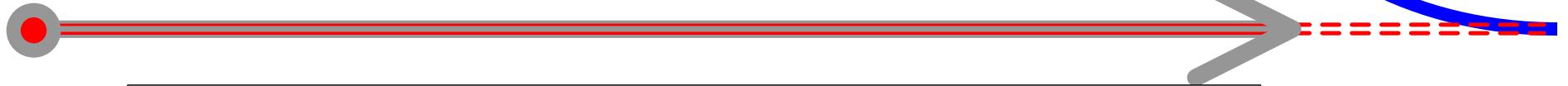
RF Fan-out for 8 GeV Linac

A. Moretti, D. Wildman

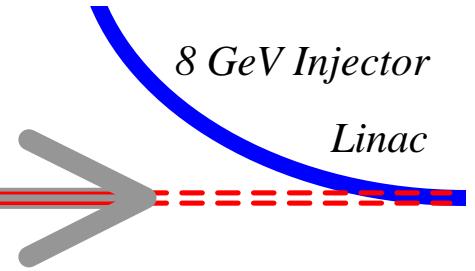




RF Power Budget & Coupler Power



RF Distribution Technical Parameters



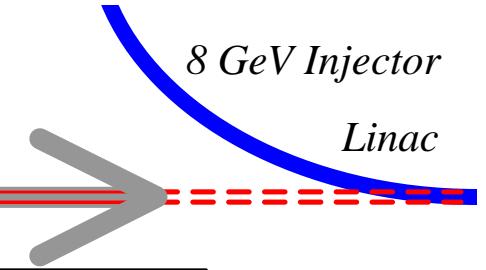
RF Distribution System	402.5 MHz	805 MHz	1207 MHz	
Peak Power from Klystron	2.5 MW	5.0 MW	10.0 MW	
Cavities per Klystron	1	8 - 12	12	
Number of Output Waveguides per Klystron	1	1	2	
Waveguides per Microwave Chase	1	2	2	
RF Distribution Efficiency (see below)	95%	87%	86%	incl. Ferrite Phase shifters
Power Available at Cavity RF Coupler	2.38 MW	0.54 MW	0.71 MW	
Peak Power Required at Coupler	1.80 MW	0.45 MW	0.60 MW	worst-case cavity in each grp.
Excess RF Power Available after losses	132%	121%	119%	TESLA ~106%
Waveguide	402.5 MHz	805 MHz	1207 MHz	
Waveguide Type (in long chase & fanout)	WR2100	WR975	WR770	local components smaller
Rated Waveguide Power @freq.	600 MW	120 MW	85 MW	
Max Power in Waveguide (at Klystron)	2.5 MW	5 MW	5 MW	
Average Power in Waveguide (at Klystron)	33 kW	75 kW	75 kW	
RF Distribution Losses	402.5 MHz	805 MHz	1207 MHz	
Average Waveguide Length	100 ft	125 ft	130 ft	incl. avg. length of fanout
Nominal Attenuation dB/100ft @freq.	0.06 db/cft	0.20 db/cft	0.25 db/cft	
Waveguide Attenuation Losses	0.06 db	0.25 db	0.33 db	Dielectric Co. Catalog
Power Splitter Directivity Losses	0.05 db	0.05 db	0.05 db	
Circulator Losses	0.10 db	0.10 db	0.10 db	0.08 meas. at TTF
Ferrite Tuner Losses	N/A	0.20 db	0.20 db	quote from AFT
Overall Losses (avg)	0.21 db	0.60 db	0.68 db	
percent power losses	5%	13%	14%	

RF - Klystrons



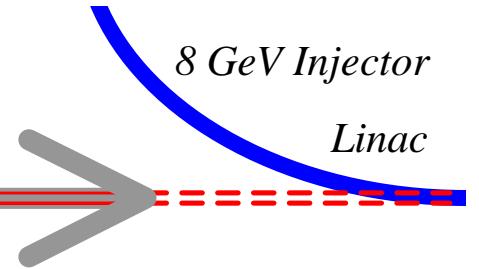
- 402.5 MHz / 2.5 MW (7 total)
 - 805 MHz / 5.0 MW (10 total)
 - 1207.5 MHz / 10 MW (36 total)
- } SNS Actual
- } TESLA Design
Scaled by ~ 7%
from 1.3GHz

Klystron Technical Parameters



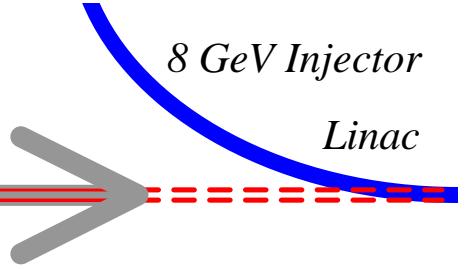
Number of Klystrons	45	linac(41) + debuncher(1) + test stands(3)		
Number of Klystron Types	3	402.5 MHz, 805 MHz, and 1207.5 MHz		
Number of Modulators	35	linac(31) + debuncher(1) + test stands(3)		
Location of Klystrons & Modulators		upstairs gallery or in side tunnel		
Klystron Individual Details	402.5 MHz	805 MHz	1207 MHz	
Number of Klystrons (main linac)	7	10	24	41 total
Number of Klystrons(test stand+debuncher)	1	1	2	4 total
Klystron System Load	DTL & RFQ	Beta<1 SCL	Beta=1 SCL	
Klystron Peak Power	2.5 MW	5 MW	10 MW	
Klystron Test Power	2.75 MW	5.5 MW	TBD	
Klystron Type	SNS	SNS	"TESLA"	* TESLA MBK modified to
Klystron Reference Manufacturer	Marconi	Thales	Thales/CPI*	* operate at 1207.5 MHz
Klystron Reference Model #	KP3525L	TH2168	TH-1801 *	* instead of 1300 MHz
Klystron RF Pulse Width	1.1 msec	1.3 msec	1.3 msec	
Klystron Repetition Rate	10 Hz	10 Hz	10 Hz	
Klystron RF Duty Cycle	1.1%	1.3%	1.3%	
Klystron Power (average)	28 kW	65 kW	130 kW	
Klystron Efficiency	50%	50%	60%	
Klystron Beam Voltage	125 kV	140 kV	117 kV	
Klystron Beam Current	40 A	71 A	142 A	
Klystron Number of Beams	1	1	7	
Klystron Perveance (Amps per V^3/2)	9.1E-07	1.4E-06	3.6E-06	
Klystron Gain	40 dB	40 dB	40 dB	
Klystron Bandwidth (1dB)	1.0 MHz	2.6 MHz	3 MHz	
Klystron Number of Internal Cavities	6	6	6	
Klystron Filament Voltage	35 V	35 V	9 V	
Klystron Filament Current	20 A	35 A	50 A	
Klystron Solenoid Power	5 kW	3 kW	5 kW	
Klystron Height	13.0 ft	13.0 ft	8.2 ft	

Klystron Cost Estimate



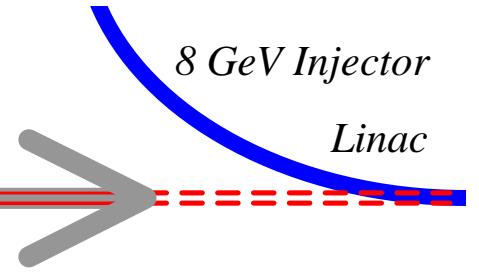
ITEM	Unit	M&S Cost \$	Quantity	M&S Tot. \$k	Eng/Mgr FTE-yr	Tech FTE-yr	Phys FTE-yr	Labor \$k	Total \$k
Klystrons				16,518	11	10	0	2,360	18,878
402.5 MHz Klystrons				2,642	4	3	0	820	3,462
402.5 MHz Prototype Klystron	ea	1,600,000	1	1,600	1			160	1,760
402.5 MHz Klystron Test Stand	ea	200,000	1	200	1	1		220	420
402.5 MHz Production Klystron	ea	104,199	8	834	1			160	994
402.5 MHz Klystron Production Test	ea	1,000	8	8		1		60	68
402.5 MHz Klystron Installation	ea				1	1		220	220
805 MHz Klystrons				1,650	3	3	0	660	2,310
805 MHz Prototype Klystron	ea		0						0
805 MHz Klystron Test Stand	ea	200,000	1	200	1	1		220	420
805 MHz Production Klystron	ea	130,849	11	1,439	1			160	1,599
805 MHz Klystron Production Test	ea	1,000	11	11		1		60	71
805 MHz Klystron Installation	ea				1	1		220	220
1207.5 MHz Klystrons				12,226	4	4	0	880	13,106
1207.5 MHz Prototype Klystron	ea	1,600,000	1	1,600	1			160	1,760
1207.5 MHz Klystron Test Stand	ea	200,000	1	200	1	1		220	420
1207.5 MHz Production Klystron	ea	400,000	26	10,400	1			160	10,560
1207.5 MHz Klystron Production Test	ea	1,000	26	26		1		60	86
1207.5 MHz Klystron Installation	ea				1	2		280	280

Modulators for Klystrons



- Biggest single component in RF costs
- Pfeffer, Wolff, & Co. (FNAL BD) have been making TESLA spec modulators for years
- FNAL Bouncer design in service at TTF since 1994

Modulator Circuit



- IGBT / Capacitor Discharge circuit
- Bouncer to maintain flat top
- Redundant Switch with Ignitron Crowbar
- Pulse Transformer 10kV to 130 kV (typ.)

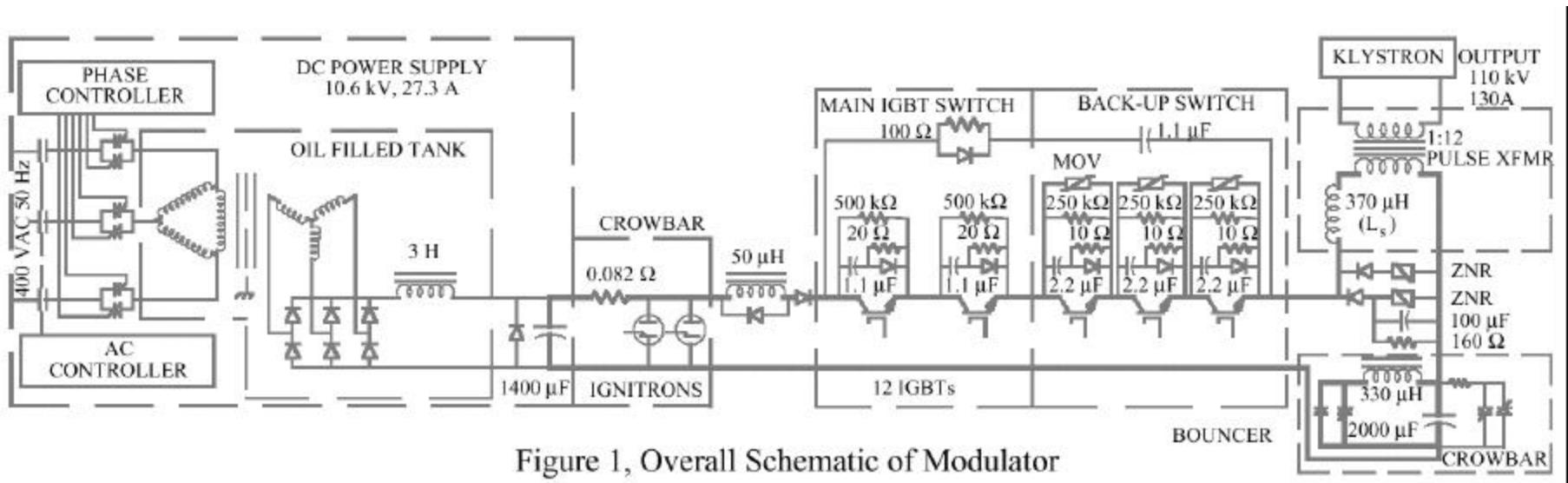
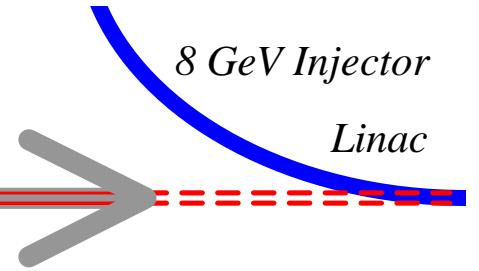


Figure 1, Overall Schematic of Modulator

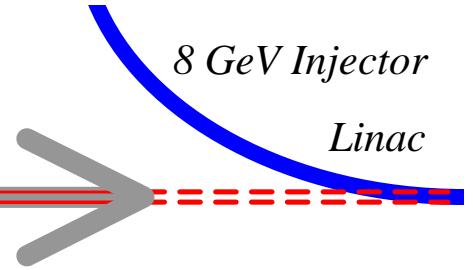
H. Pfeffer, D. Wolff, & sons.

Modulator Cost Estimate



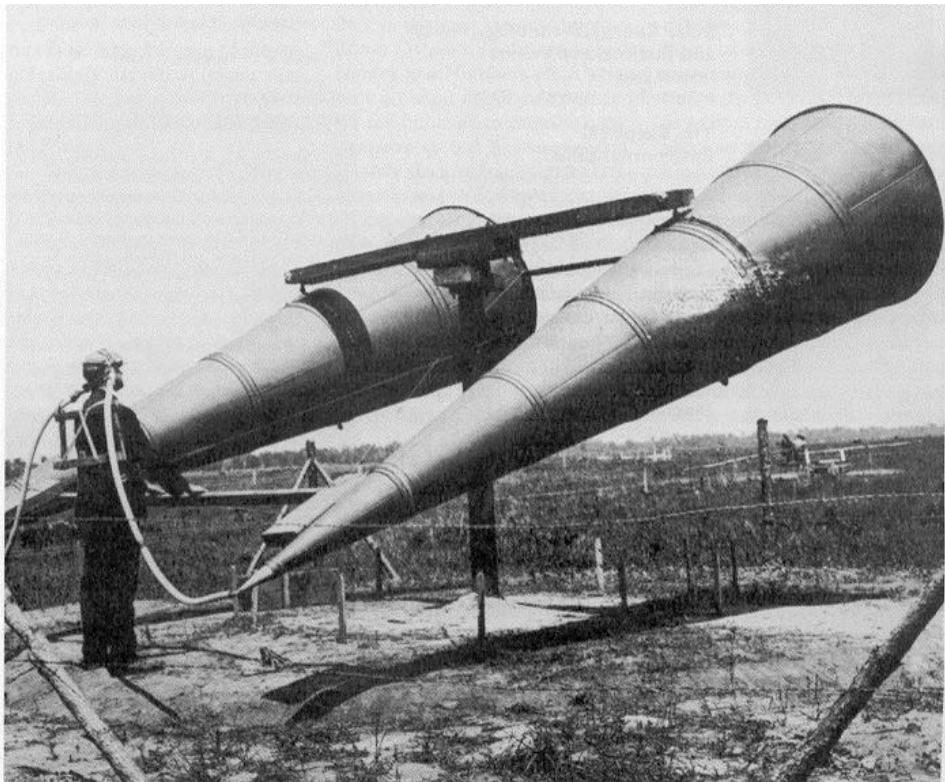
ITEM	Unit	M&S Cost \$	Quantity	M&S Tot. \$k	Eng/Mgr FTE-yr	Tech FTE-yr	Phys FTE-yr	Labor \$k	Total \$k
Modulators & Pulse Transformers									
Modulators (no Pulse Transf.)	ea	505,416	33	16,679	6	4		1,200	17,879
Modulator Parts	ea	258,096	33	8,517	3			480	258,576
Power Transformer	ea	46,400	33	1,531					46,400
IGBT Switch including Backup	ea	26,400	33	871					26,400
Modulator Controls	ea	22,120	33	730					22,120
Main Cap Bank	ea	18,768	33	619					18,768
Power Line Conditioning	ea	18,560	33	612					18,560
Cabinet	ea	8,920	33	294					8,920
SCR Controller	ea	6,496	33	214					6,496
Machine shop	ea	6,496	33	214					6,496
Bouncer Choke	ea	5,568	33	184					5,568
Bouncer Caps	ea	5,568	33	184					5,568
Power Resistors	ea	5,568	33	184					5,568
Klystron Filament PS	ea	4,640	33	153					4,640
Solenoid PS	ea	4,640	33	153					4,640
480VAC Contactor	ea	3,712	33	122					3,712
HV Diodes	lot	3,712	33	122					3,712
Ignitron Tubes	ea	3,712	33	122					3,712
Other Misc. Parts	ea	66,816	33	2,205					66,816
Assembly Labor & vendor profit	ea	237,320	33	7,832	2			320	237,640
Installation (electrician)	ea	10,000	33	330	1			160	10,160
Test in situ	ea					4		240	240
Pulse Transformers & Oil Tanks									
Pulse Transf. 402 MHz Klystron	ea	107,741	8	862	1	1		220	1,082
Pulse Transf. 805 MHz Klystron	ea	105,235	11	1,158	1	1		220	1,378
Pulse Transf. 1207 MHz Klystron	ea	98,971	26	2,573	1	2		280	2,853
Klystron Modulator Ancillary Equpt.				270	1	1		220	490
Oil Handling Equipment	cart	30,000	4	120	0.5			80	200
Klystron Installation/Transport Device	ea	15,000	10	150	0.5	1		140	290

RF Phasing in Linac for Protons vs. Electrons



- Cavity cell length changes as proton accelerates
 - not all cavities can be same design
 - lose some gradient by running off design β
- Protons are non-relativistic
 - energy error \Rightarrow downstream phase error
- Protons run off-crest
 - only get $\sim 85\%$ of accelerating gradient at crest
 - more sensitive to phase errors
- Must change cavity phases to accelerate electrons and protons on alternate cycles

CAVITY MICROPHONICS



World War I Aircraft Detection

Within days of U.S. entry into World War I in April 1917, the Navy requested the National Research Council's help in developing a method for detecting and locating aircraft. The Research Council passed the problem along to George W. Stewart, head of the

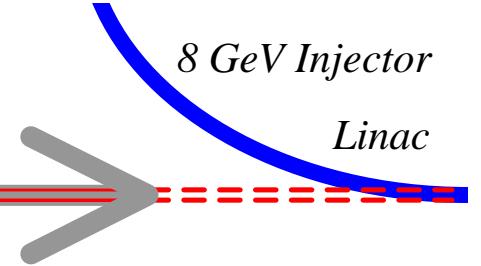
physics department at the State University of Iowa. After some experimentation, Stewart designed a set of 18-foot-long listening horns, which were supposed to provide anti-aircraft and searchlight batteries with early warning of distant enemy aircraft. Stewart's device

never made it past the experimental stage; for field use, the American Expeditionary Forces adapted an aircraft sound locator purchased from the French. This photo shows a set of these horns undergoing trials at Ellington Field, outside of Houston, Texas, in Spring 1918.

ISSUES IN SCIENCE AND TECHNOLOGY

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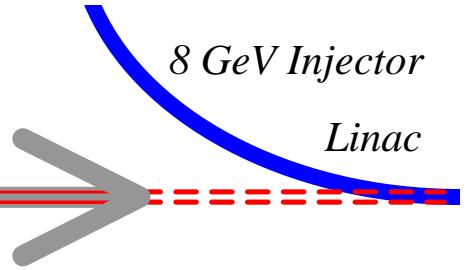
G. W. Foster 14 May '02



- Cavity Bandwidths are $\sim 1 \text{ kHz}$ ($Q \sim 10^6$)
- Mechanical vibrations can shift resonant freq. by comparable amount.
- Produces large shift in required *phase* and *amplitude* of RF drive
- Codes exist to simulate impact on proton beams from measured (SNS/TESLA) microphonics.

66

Tuners and Cavity Resonance Control



- TESLA R&D has shown that piezoelectric tuners can correct for Lorentz detuning and cavity microphonics in a 1 ms pulsed SC linac.
- SNS Cavity assemblies used for cost basis include *both* Mechanical and Piezoelectric tuners
- RF phase and amplitude control provided for individual cavities via fast ferrite phase shifters.
- Simulation (& SNS experience) needed to determine bandwidth requirement of shifters.

Fast Ferrite Phase Shifter R&D

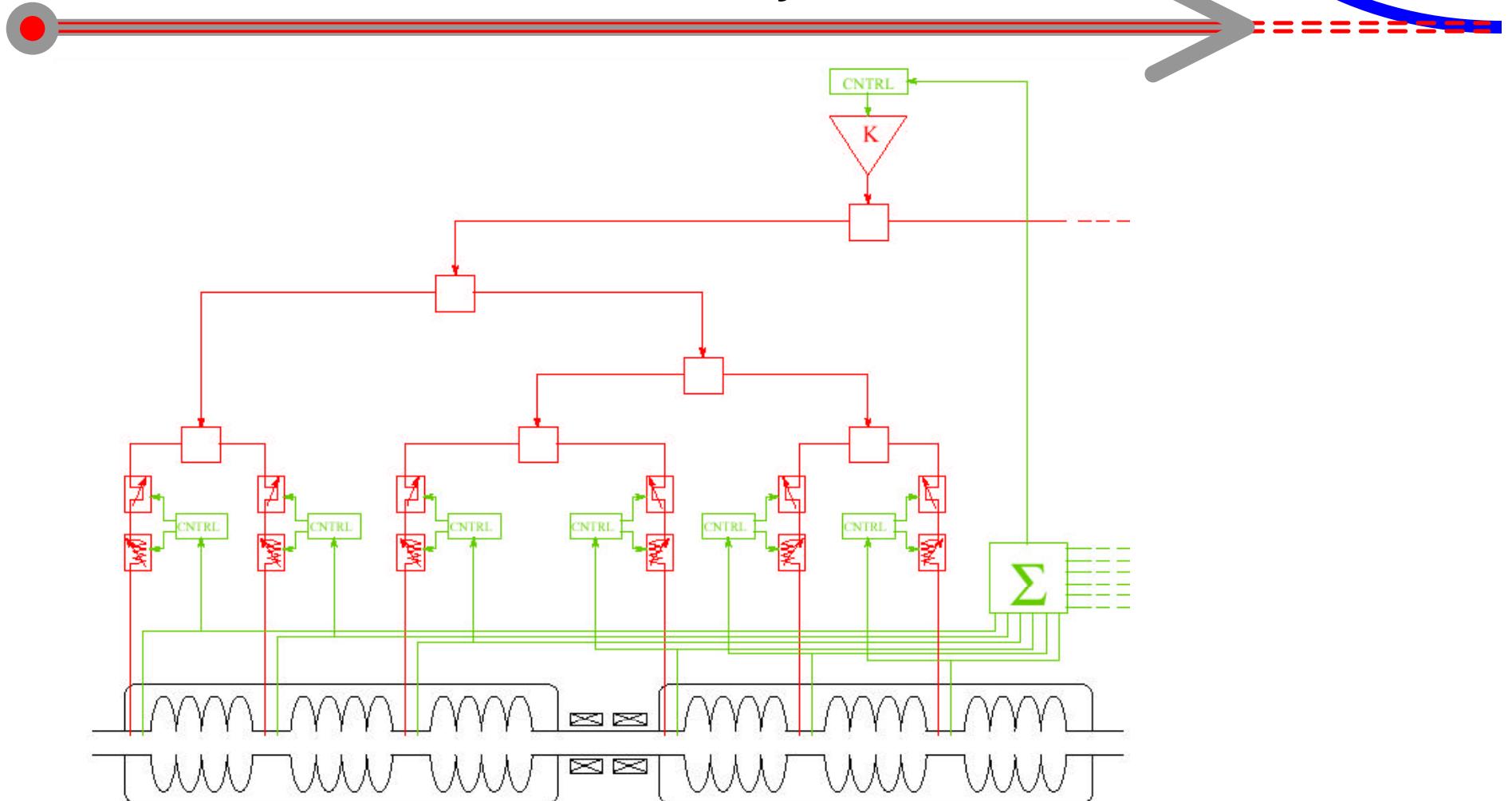


- Provide fast, flexible drive to individual cavities of a proton linac, when one is using TESLA-style RF fanout.
- Also needed if Linac alternates between e and P.
- The fundamental technology is proven in phased-array radar transmitters.
- This R&D was started by SNS but dropped due to lack of time. They went to one-klystron-per-cavity which cost them a lot of money (~\$20M).

“SNS March 2000” Design, 12 Cavities / Klystron Individual + Collective Cavity Control

8 GeV Injector

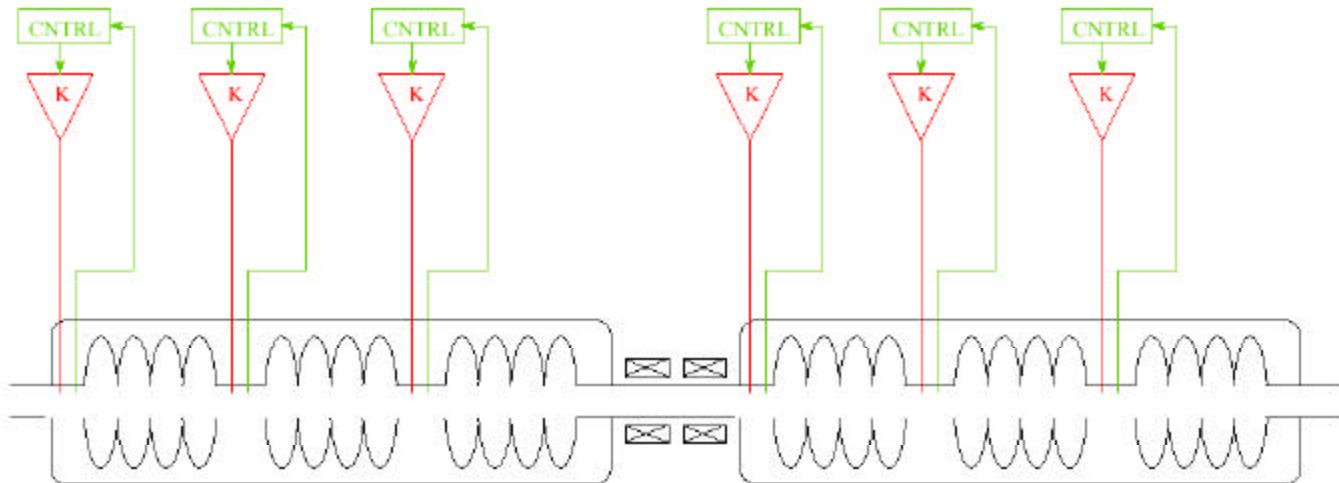
Linac



- SNS pursued & dropped due to lack of R&D time

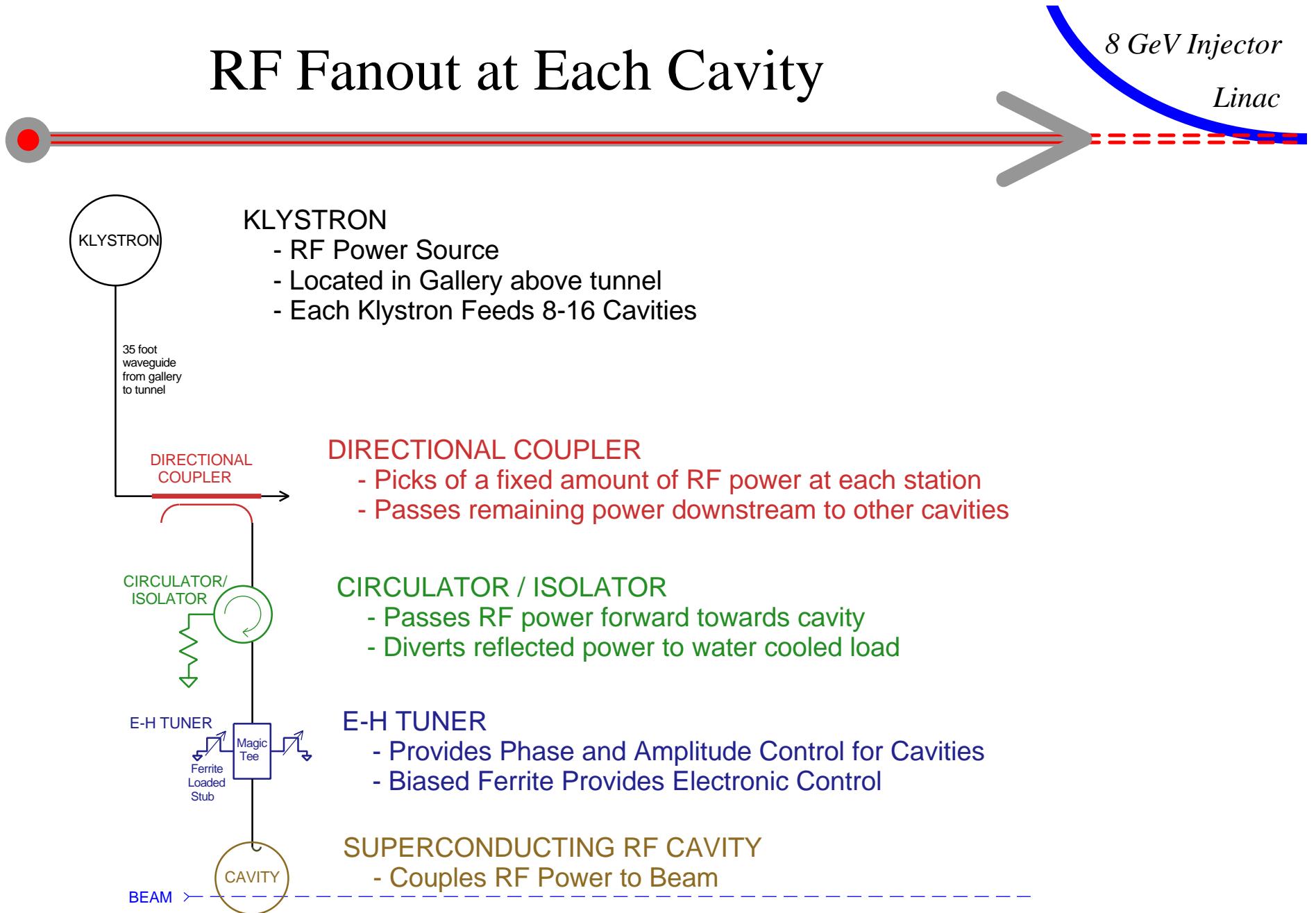
SNS Final Baseline RF Design

1 Klystron Per Cavity, Individual Control



- Conceptually simpler but ~10x more Klystrons

RF Fanout at Each Cavity



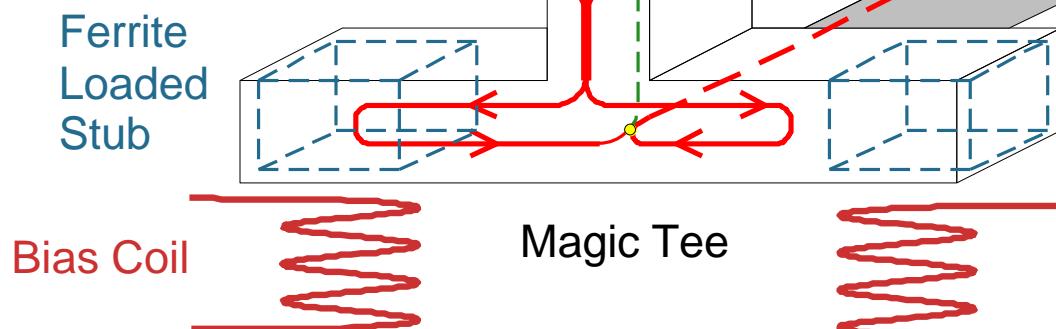
ELECTRONICALLY ADJUSTABLE E-H TUNER



MICROWAVE INPUT POWER
from Klystron and Circulator

E-H TUNER

ELECTRONIC TUNING
WITH BIASED FERRITE



ATTENUATED
OUTPUT
TO CAVITY

Attractive
Price Quote
from AFT
(<< Klystron)

FERRITE LOADED
SHORTED STUBS
CHANGE ELECTRICAL
LENGTH DEPENDING
ON DC MAGNETIC BIAS.

TWO COILS PROVIDE INDEPENDENT
PHASE AND AMPLITUDE CONTROL OF CAVITIES

Phase and Amplitude Tuner Specs

8 GeV Injector

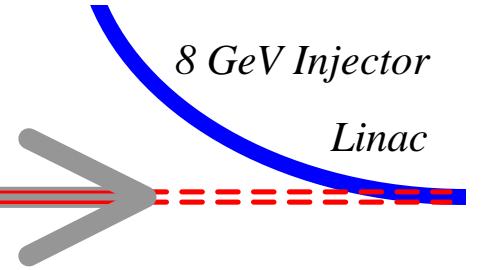
Linac



RF Phase and Amplitude Adjustment	402.5 MHz	805 MHz	1207 MHz	
Phase / Amplitude Tuner Type	LLRF	Ferrite	Ferrite	
Phase / Amplitude Tuner Locations	1 / klystron	1 / cavity	1 / cavity	
Number of Phase / Amplitude Tuners	7	96	300	
Phase Tuner Adjustment Range (deg)	> 360 deg	400 deg	400 deg	for running electrons and H-
Phase Tuner Slew Rate	>360deg/us	1 deg/usec	1 deg/usec	target
Amplitude Tuner Attenuation Range	~inf	-10dB	-10dB	target
Amplitude Tuner Slew Rate	>20db/usec	~0.1dB/usec	~0.1dB/usec	target TBD, varies w/setting
Phase Tuner Peak Power	-	0.45 MW	0.60 MW	
Phase Tuner Insertion Loss	-	0.2 db	0.2 db	AFT quote
Phase Tuner VSWR Loss	-	0.02 db	0.02 db	target
Phase Tuner Avg. RF Power Dissipation	-	263 W	351 W	target
Phase Tuner Coil Average Power Dissipation	-	40 W	40 W	target for 10Hz pulse rep rate
Static RF amplitude error	+/-1%	+/-1%	+/-1%	TBD
Static RF phase error	+/-1 deg.	+/-1 deg.	+/-1 deg.	TBD
Dynamic RF amplitude error	+/-0.5%	+/-0.5%	+/-0.5%	TBD
Dynamic RF phase error	+/-0.5 deg.	+/-0.5 deg.	+/-0.5 deg.	TBD

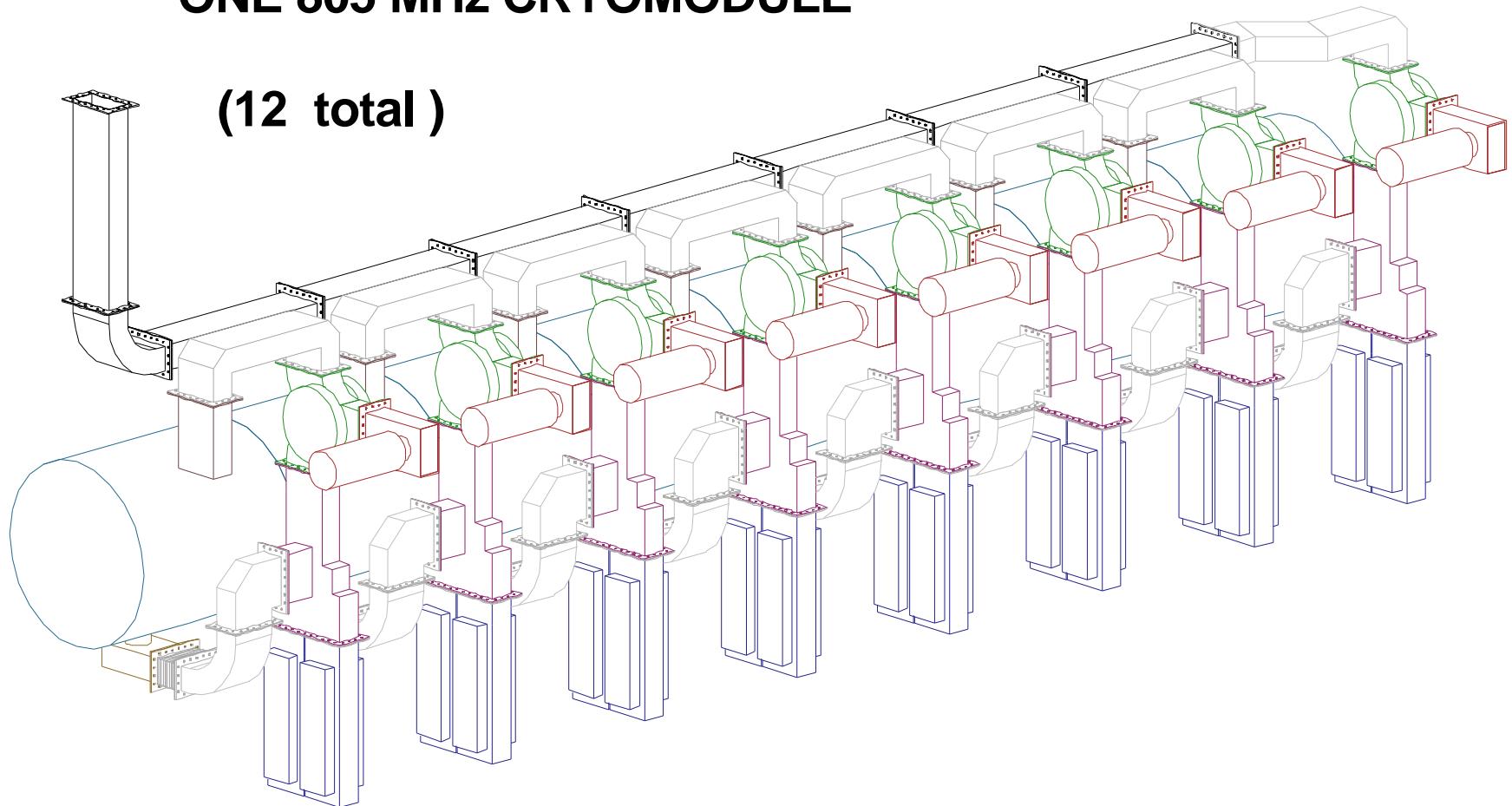
...tuner bandwidth has significant impact on cost

805 MHz RF Distribution in Tunnel



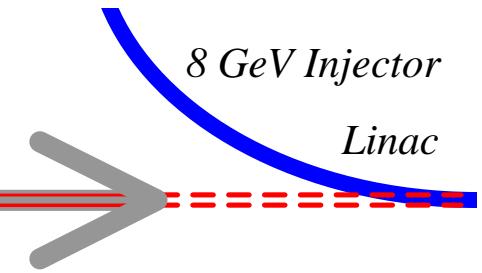
**RF DISTRIBUTION FOR
ONE 805 MHz CRYOMODULE**

(12 total)



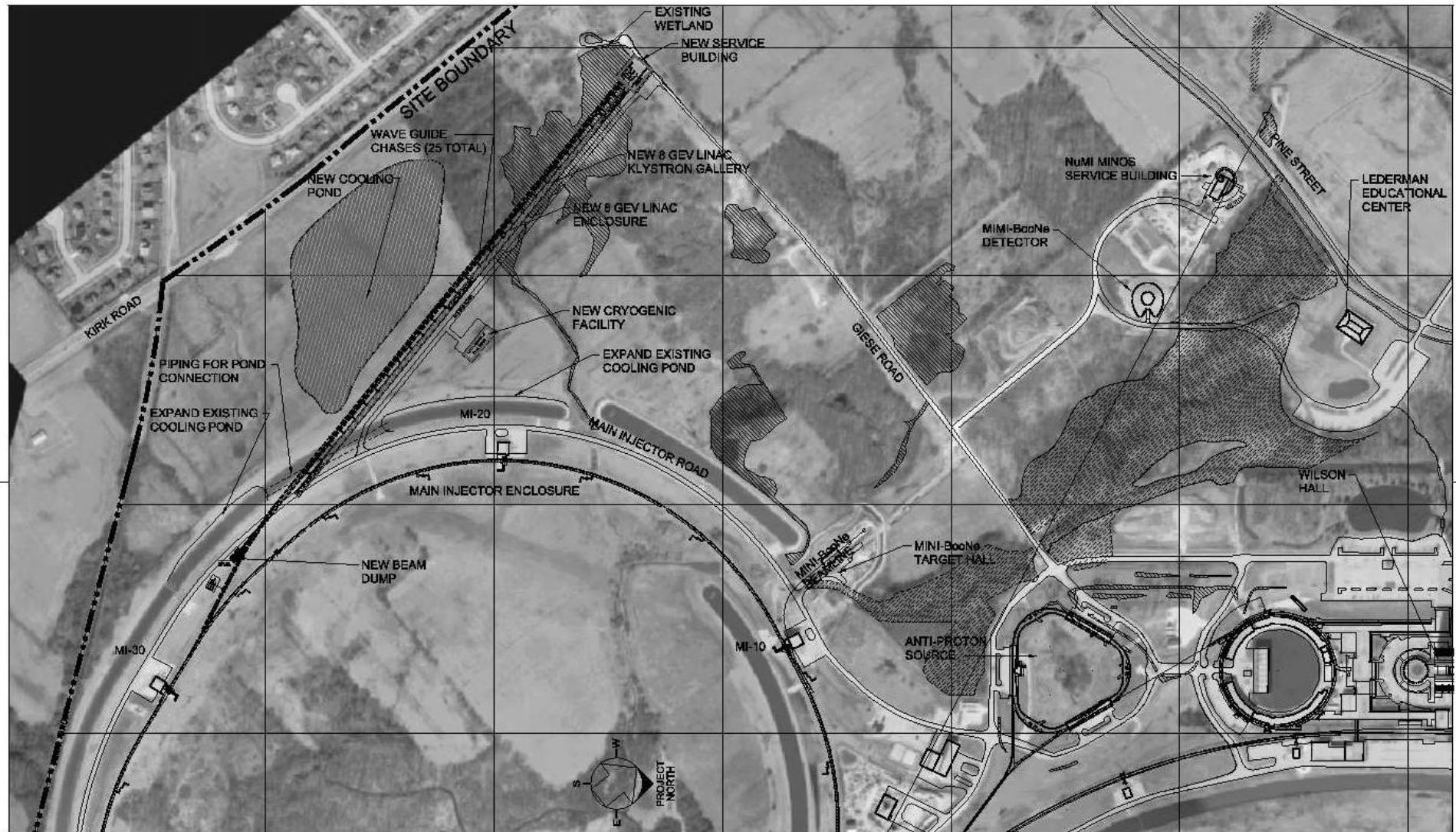
WAVEGUIDE TUNER OPTION

RF Distribution Cost Estimate



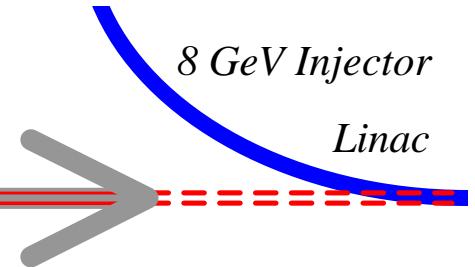
ITEM	Unit	M&S Cost \$	Quantity	M&S Tot. \$k	Eng/Mgr FTE-yr	Tech FTE-yr	Phys FTE-yr	Labor \$k	Total \$k
RF Distribution				34,287	12	28	0	3,600	37,887
402.5 MHz RF Distribution				1,207	2	4	0	560	0
805 MHz RF Distribution				9,437	4	10	0	1,240	0
1207.5 MHz RF Distribution				23,643	6	14	0	1,800	0
Components per 1207 MHz Klystron			26	418		2	4	0	560
WR650 H-mitre on Klystron Output	ea	421	52	22					22
Fwd&Rev Power Monitors at Klystron	ea	976	52	51					51
WR650 30-degree E-sweep (down bend)	ea	438	52	23					23
WR650 20ft Straight Guide (through chase)	ea	1,952	52	102					102
WR650 30-degree E-sweep (up bend)	ea	438	52	23					23
WR650 Straight Guide (Tunnel Traverse)	ea	390	52	20					20
WR650 H-mitre (bend parallel to beam line)	ea	421	52	22					22
Space Frame for 1207 MHz Fanout	ea	2,500	52	130					130
WR650 misc. gaskets, hangers, etc.	ea	1,000	26	26					26
Components per 1207 MHz Cavity		1,000	312	23,226		2	10	0	920
WR650 Sidewall Couplers (8 varieties)	ea	3,756	312	1,172					1,172
WR650 misc. Straight Waveguides	ea	732	312	228					228
E-miter Panty for Directional Coupler	ea	659	624	411					411
Reverse Power Load (air cooled)	ea	2,500	312	780					780
Dual RF Power Monitor (circulator input)	ea	976	312	305					305
1207 Circulators 0.6 MW pk, 150kW avg	ea	11,500	312	3,588					3,588
Dual RF Power Monitor (on water load)	ea	976	312	305					305
1207 MHz Water Loads	ea	4,000	312	1,248					1,248
1207 Ferrite Tuner Including Magic Tee	ea	45,000	312	14,040					14,040
Dual RF Power Monitor (cavity)	ea	976	312	305					305
WR650 Flex Waveguide	ea	1,707	312	533					533
WR650 misc. gaskets, hangers, etc.	ea	1,000	312	312					312

8 GeV Linac - Siting for Design Study (FESS)



		NAME	DATE	SCALE:	400	0	400	800	FERMI NATIONAL ACCELERATOR LABORATORY
		DESIGNED		1" = 400'-0"	SCALE				UNITED STATES DEPARTMENT OF ENERGY
		DRAWN							
		CHECKED							
		APPROVED							
REV.	DATE	DESCRIPTIONS	SUBMITTED						8 GEV LINAC STUDY
		REVISIONS							SITE PLAN
									DRAWING NO. 6-9-3 TDR-1 REV.

Civil Construction Cost Estimate



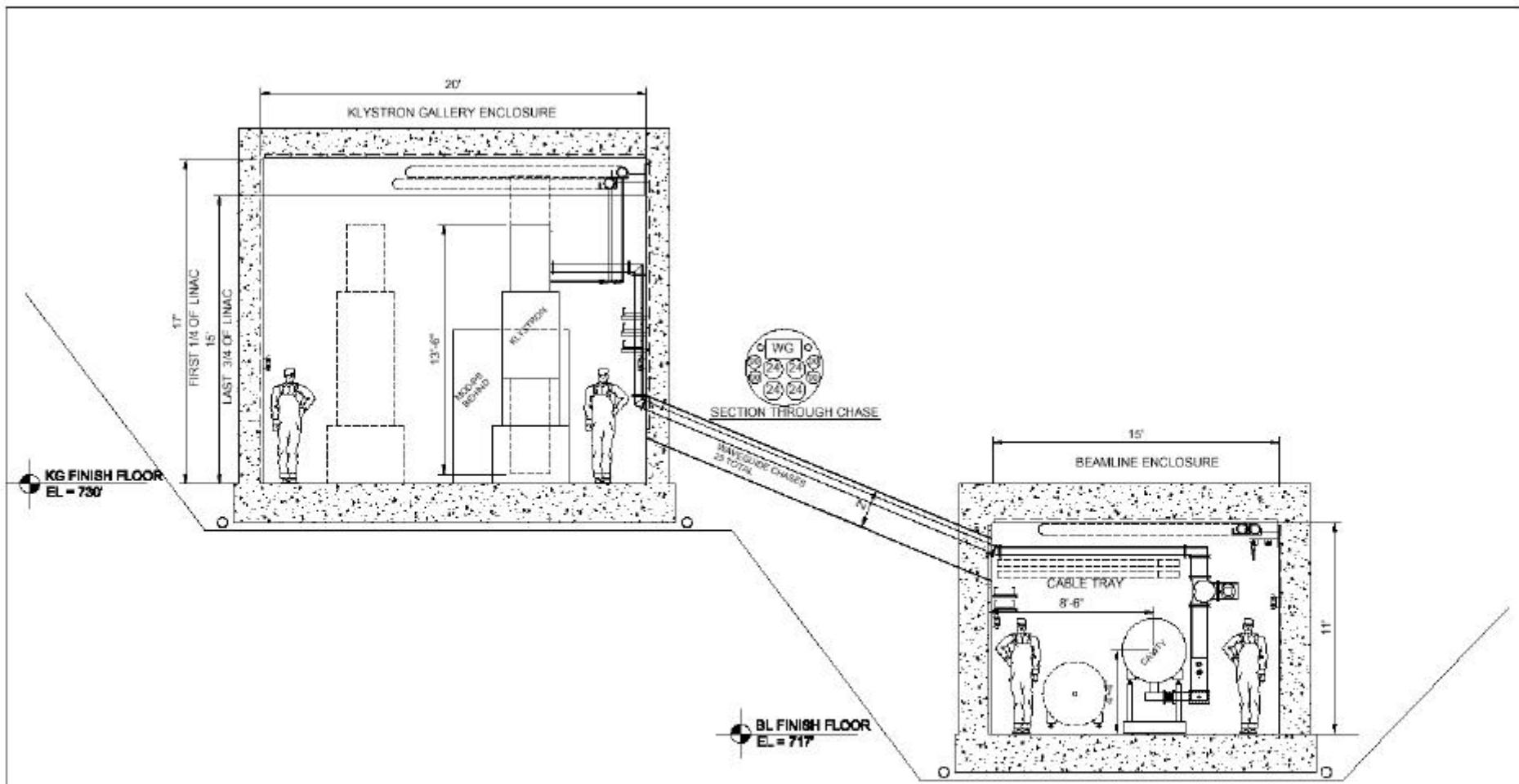
ITEM	Unit	M&S Cost \$	Quantity	M&S Tot. \$k	Eng/Mgr FTE-yr	Tech FTE-yr	Phys FTE-yr	Labor \$k	Total \$k
Civil Construction				44,361	71	8		11,840	56,201
Construction Management						68		10,880	10,880
Site Work				7,085					7,085
Utilities				5,300	3	8		960	6,260
Beamline Tunnel Enclosure	If	3,592	3200	11,494					11,494
Klystron Gallery	If	3,264	2300	7,506					7,506
Front End Building				4,113					4,113
Dump Enclosure				250					250
Cryogenics/ICW HTX Facility				7,093					7,093
Debuncher Building (Optional)				1,520					1,520

\$56M (x 1.3 conting.) = \$73M

Main Injector Actual Civil Construction Costs vs. 8 GeV Linac Estimate



	Main Injector (Lackowski)	8 GeV Linac Estimate	%
Tunnel Length (m)	4000 m	1700 m	43%
Surface Buildings (sq. ft.)	60,000 sq.ft.	29,000 sq.ft.	48%
Surface Area for Site Prep Work	~ 50 Acres	~ 25 Acres	50%
Excavated Volume (cu Yards)	475,000 cu.yd.	400,000 cu.yd.	84%
Concrete Volume (cu yards)	40,000 cu.yd.	30,000 cu.yd.	75%
Line Power & Heat Rejection (MW)	22 MW	12 MW	55%
Total Civil Cost	\$103 M (S. Holmes)	\$73 M (FY'02) incl 30% conting.	71%



TYPICAL SECTION THROUGH LINAC

SHOWING 805 MHZ KLYSTRON AND CAVITY

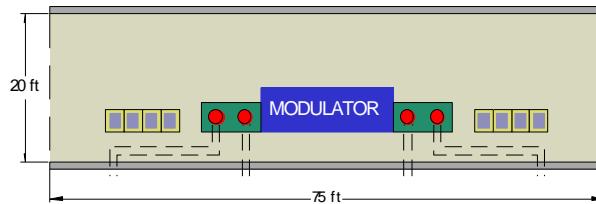
		NAME	DATE	SCALE:	FERMI NATIONAL ACCELERATOR LABORATORY	
DESIGNED				1" = 5'-0"	UNITED STATES DEPARTMENT OF ENERGY	
DRAWN				SCALE	8 GEV LINAC STUDY	
CHIEF DRAFTER					CROSS SECTIONS	
APPROVED					DRAWING NO.	6-9-3
REV.	DATE	DESCRIPTIONS	RELEASING TO			TDR-3
		REVISED				REV.

8 GeV Klystron Gallery Floor Plan

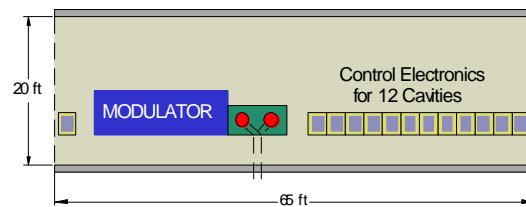


RF STATIONS IN KLYSTRON GALLERY (to scale)

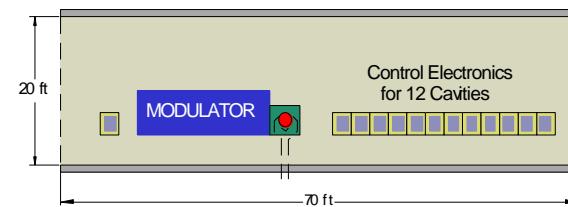
402.5 MHz (2 Stations, 4 Klystrons ea.)



805 MHz (5 Stations, 2 Klystrons ea.)

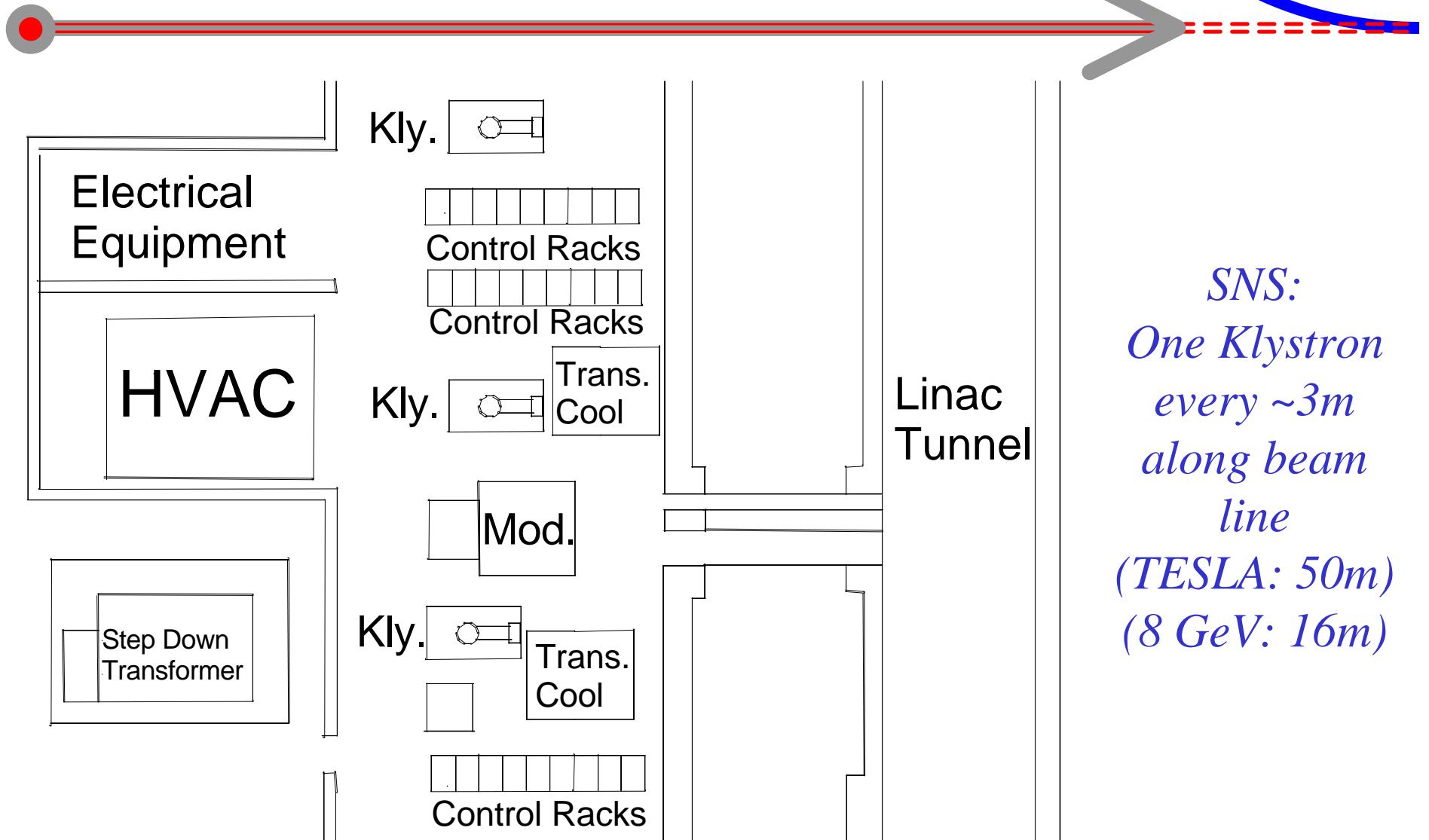


1207.5 MHz (24 Stations, 1 Klystron ea.)



- Linear array of equipment - simpler than SNS
- Much more room allocated for electronics than TESLA design

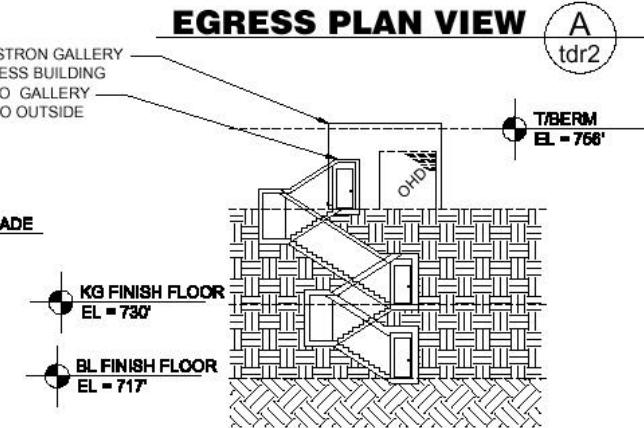
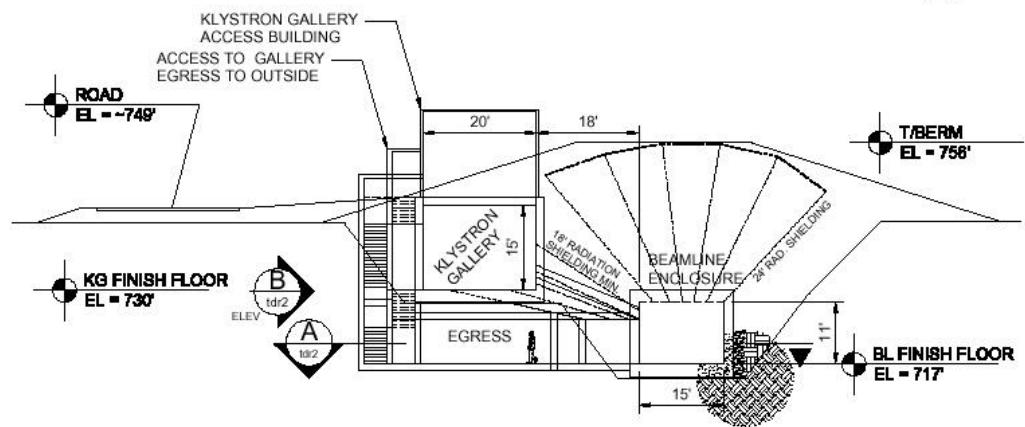
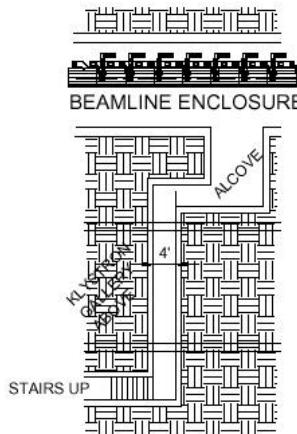
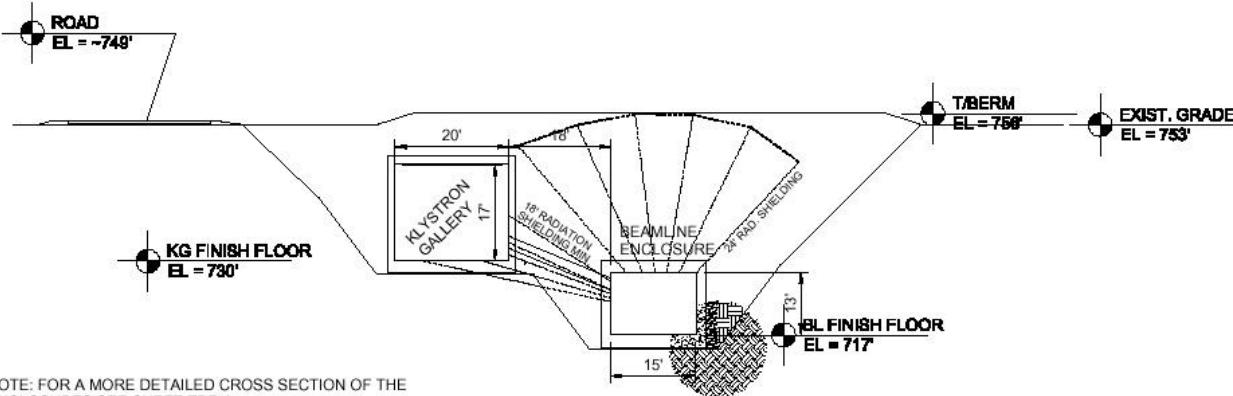
SNS Tunnel & Klystron Gallery



Note on Klystron Location

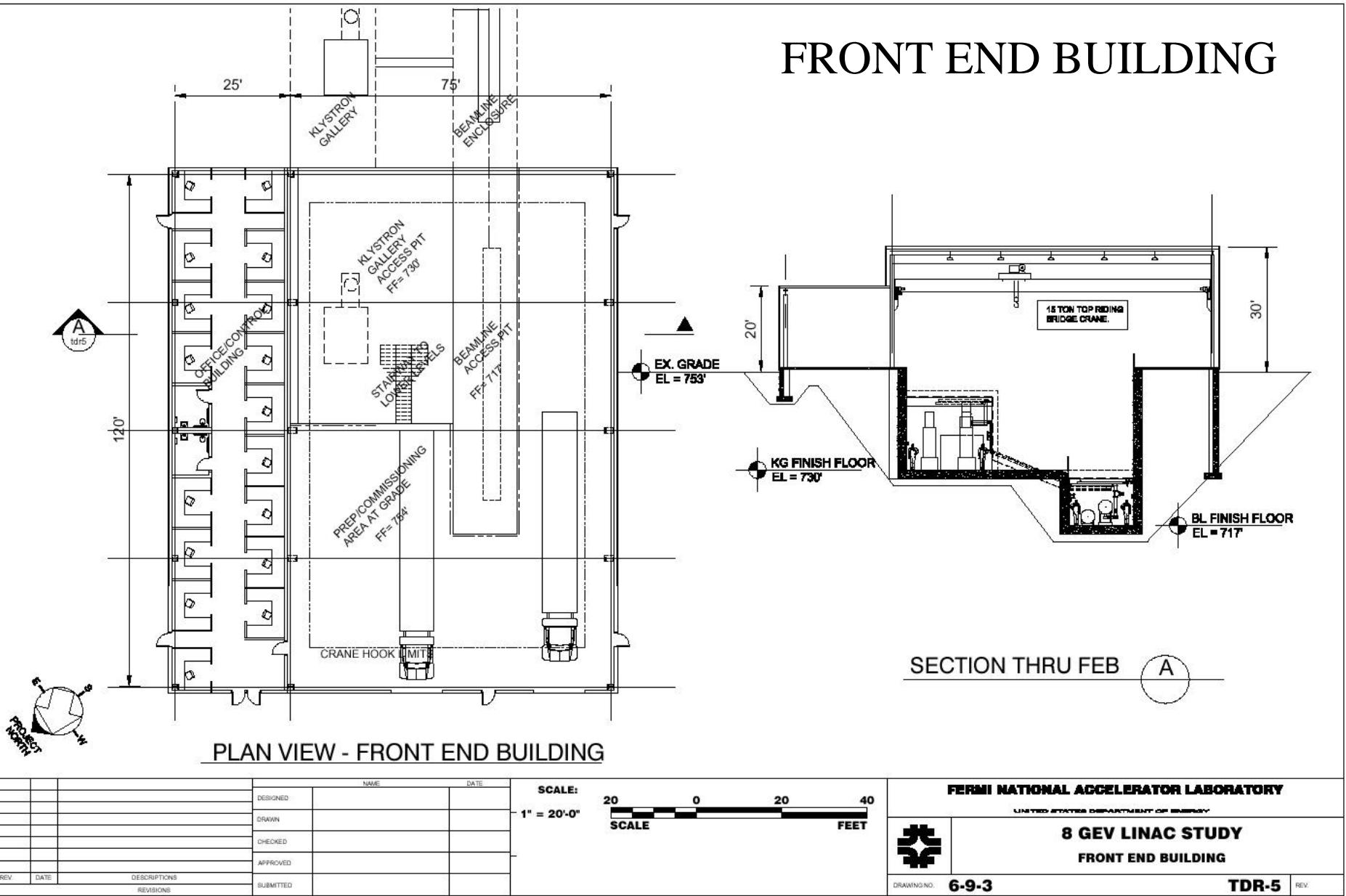


- The Civil Construction (Klystron Gallery) costs could be reduced a lot if we adopt the TESLA scheme of putting the Klystron and instrumentation electronics in the tunnel, and running a fat cable to a single building with all of the modulators in it.
- This may not be an acceptable technical risk.

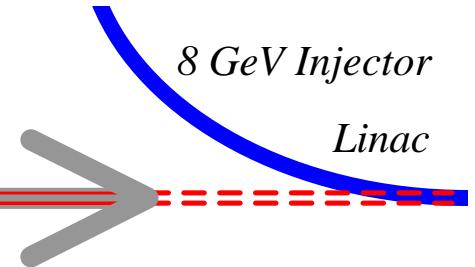


		NAME	DATE	SCALE:	FERMI NATIONAL ACCELERATOR LABORATORY			
	DESIGNED			1" = 20'-0"	20	0	20	40
	DRAWN			SCALE	UNITED STATES DEPARTMENT OF ENERGY			
	CHECKED				8 GEV LINAC STUDY			
	APPROVED				CROSS SECTIONS			
REV.	DATE	DESCRIPTIONS	SUBMITTED		DRAWING NO.	6-9-3	TDR-2	REV.
		REVISIONS						

FRONT END BUILDING

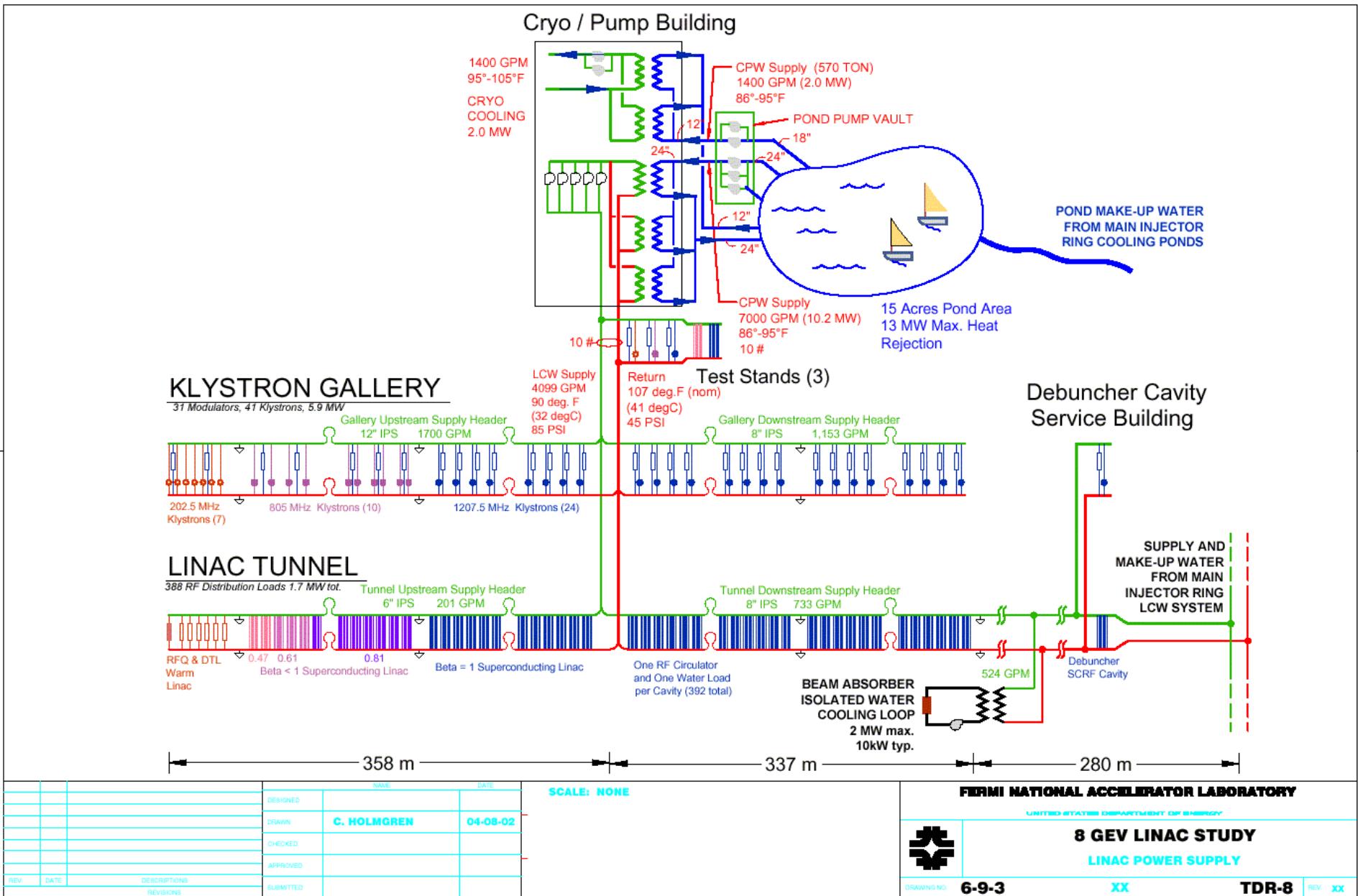


Front End Building Cost Estimate

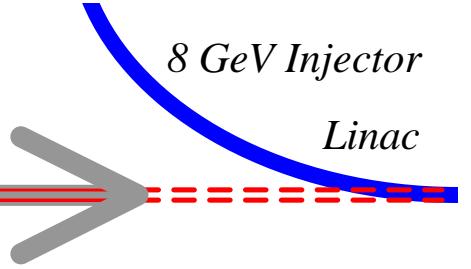


Cost Model is Main Injector MI-60 Service Building

ITEM	Unit	M&S Cost \$	Quantity	M&S Tot. \$k	Eng/Mgr FTE-yr	Tech FTE-yr	Phys FTE-yr	Labor \$k	Total \$k
Front End Building				4,113					4,113
Front-End High Bay	sf	300	9000	2,700					2,700
Frame									
Roof and walls									
Finishing									
Concrete Floor									
Electrical Outfitting									
Fire Protection									
HVAC									
Crane									
Office Space in Front End Bldg.	sf	200	3000	600					600
Frame									
Roof and walls									
Finishing									
Concrete Floor									
Electrical Outfitting									
Fire Protection									
HVAC									
Excavation	ls	100,000	1	100					100
Below grade structural concrete	ls	500,000	1	500					500
Utilities	ls	150,000	1	150					150
Bituminous Parking Lot	sy	25	2500	63					63



Cooling Water (LCW) Loads



GALLERY LCW LOADS		8 GeV Linac			
402.5 MHz RF STATION					
Number of Modulator Rf Stations		2			
Modulator Chassis	46 kW	43.8 l/m	11.6 GPM	15 degC	
Pulse Transformer	3 kW	2.9 l/m	0.8 GPM	15 degC	
Number of Klystrons/modulator		3.5			on average
Klystron Collector	28 kW	113.6 l/m	30.0 GPM	3 degC	
Klystron Body	8 kW	9.1 l/m	2.4 GPM	15 degC	
Klystron Solenoid	5 kW	10.0 l/m	2.6 GPM	15 degC	
RF Station Total	191 kW	510.92 l/m	135.0 GPM	15 degC	
Total all 402.5 MHz RF Stations In Gallery	381 kW	1021.8 l/m	270.0 GPM	5.3 degC	
805 MHz RF STATION					
Number of Modulator Rf Stations		5			
Modulator Chassis	53 kW	50.6 l/m	13.4 GPM	15 degC	
Pulse Transformer	3 kW	2.9 l/m	0.8 GPM	15 degC	
Number of Klystrons/modulator		2			
Klystron Collector	65 kW	110.0 l/m	29.1 GPM	8 degC	
Klystron Body	8 kW	7.6 l/m	2.0 GPM	15 degC	
Klystron Solenoid	3 kW	2.9 l/m	0.8 GPM	15 degC	
RF Station Total	208 kW	294.46 l/m	77.8 GPM	15 degC	
Total for all 805 MHz RF Stations In Gallery	1040 kW	1472 l/m	389.0 GPM	10.1 degC	
1207 MHz RF STATION					
Number of RF Stations		24	Linac+debuncher		
Modulator Chassis	44 kW	42.1 l/m	11.1 GPM	15 degC	
Pulse Transformer	3 kW	2.9 l/m	0.8 GPM	15 degC	TESLA TDR
Klystron Collector	103 kW	250.0 l/m	66.1 GPM	6 degC	Thales
Klystron Body	8 kW	10.0 l/m	2.6 GPM	11 degC	Thales
Klystron Solenoid	5 kW	10.0 l/m	2.6 GPM	7 degC	Thales
RF Station Total	163 kW	315.0 l/m	83.2 GPM	7.4 degC	
Total for all 1207 MHz RF Stations In Gallery	3915 kW	7560.4 l/m	1997 GPM	7.4 degC	
TUNNEL LCW LOADS		8 GeV Linac			
DTL + RFQ Cooling Load in Tunnel		193 kW	184 l/m	49 GPM	15.0 degC
TUNNEL CAVITY STATION (1207 MHz)					
Number of Cavity RF Stations in Tunnel		392	One Circuit for (Circulator + Ferrite Tuner +Water Load Absorber) in s assume all stations are like 1207 MHz (pessimistic)		
Circulator	0.2 kW				
Ferrite Tuners	0.4 kW		sum of 2 tuners with 0.2dB total losses		
Water Load	3.6 kW				
Total per Cavity	4.1 kW	4.0 l/m	1.0 GPM	15 degC	
Total for all Cavity Stations in Tunnel	1623 kW	1550.5 l/m	409.6 GPM	15.0 degC	
BEAM DUMP RAW System		2075 kW	1982 l/m	524 GPM	15 degC
Beam Stop Location	Along Transfer Line to Ring				
Pump & Heat Exchanger Location	In Beam Dump Enclosure				
Beam Heat Load (design)	2 MW		worst case during comissioning		
Beam Heat Load (typical)	<10 kW		typical during running		
RAW Pump Heat Load	75 kW		100 HP WAG		
Heat Exchanger	With Downstream LCW flow in tunnel				

- System designed for 15 degC Maximum Temperature Rise

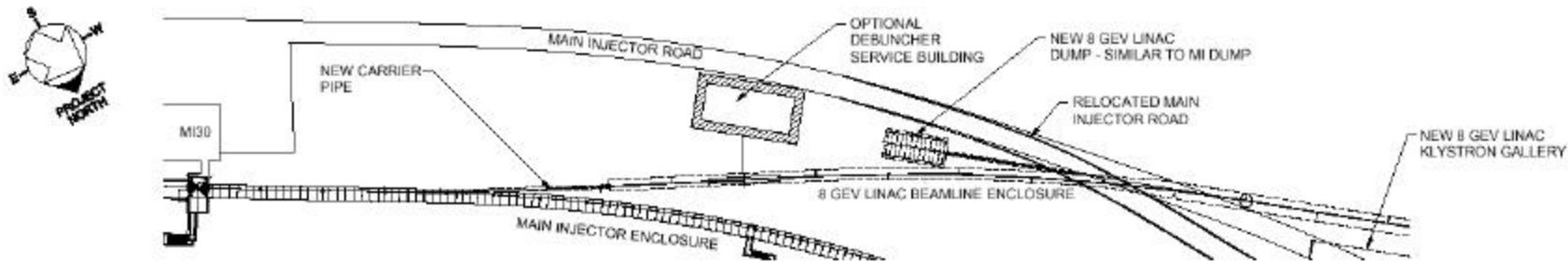
Site Work & Utilities: \$13M x 1.3 = \$17.3M

8 GeV Injector
Linac

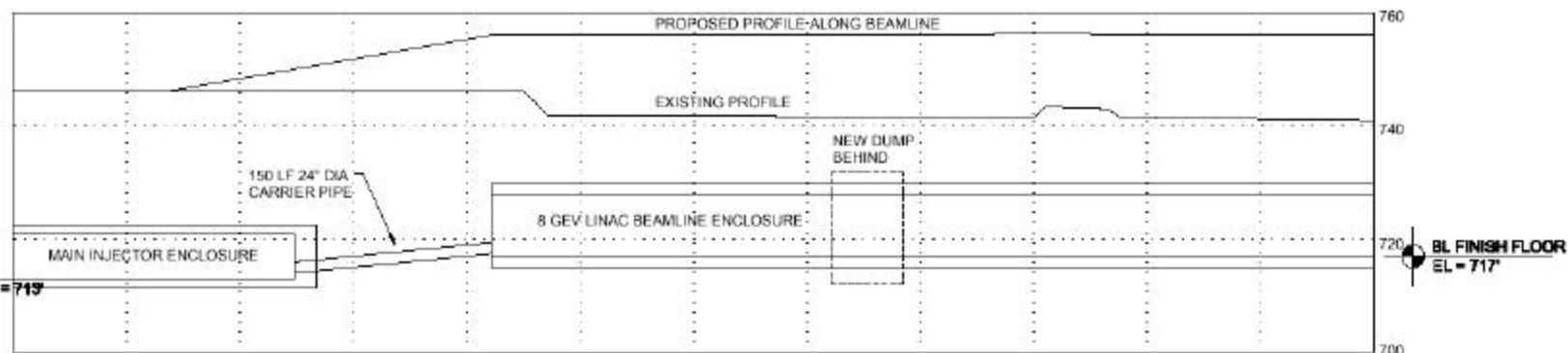


ITEM	Unit	M&S Cost	Quantity	M&S Tot.	Eng/Mgr	Tech	Phys	Labor	Total
		\$		\$k	FTE-yr	FTE-yr	FTE-yr	\$k	\$k
Site Work				7,085					7,085
Surface Work				4,735					4,735
Wetland Mitigation	acre	100,000	5	500					500
Erosion Control	ls	4,000,000	1	4,000					4,000
Stream Rerouting	acre	100,000	1	100					100
Topsoil Stripping	acre	3,000	25	75					75
Fine Grading and Seeding	acre	3,000	20	60					60
Roads				700					700
Temporary Roadway Including Signage	If	100,000	1	100					100
Bituminous Pavement w/ base for Roads	sy	25	18000	450					450
MI road realignment	ls	150,000	1	150					150
Cooling Ponds				1,650					1,650
Pond Excavation	cy	5	150000	750					750
Pond Embankment	cy	5	80000	400					400
Pond Lining	sy	4	75000	300					300
MI Pond Expansion	ls	200,000	1	200					200
Utilities				5,300	3	8		960	6,260
Electrical				2,600					2,600
Duct Bank Extension	If	100	4000	400					400
Electrical Feeder	If	100	20000	2,000					2,000
Telecom	sys	200,000	1	200					200
LCW Systems in Enclosures				600	3	8		960	1,560
Klystron Gallery LCW				300	1	4		400	700
Linac Tunnel LCW				250	1	3		310	560
Beamline Tunnel LCW				50	1	2		250	300
Other Piping Systems				2,100					2,100
ICW Piping	If	1,500,000	1	1,500					1,500
Gas Piping	If	200,000	1	200					200
DWS and Sanitary Sewer Extension	If	100	4000	400					400
MI Pond Piping	ls	100,000	1	100					100

MAIN INJECTOR CONNECTION



PLAN



PROFILE ALONG 8 GEV LINAC

REV.	DATE	DESCRIPTION	REVISIONS	NAME	DATE
				DESIGNED	
				DRAWN	
				CHECKED	
				APPROVED	

SCALE: 100 0 100 200
1" = 100'-0" HORIZONTAL FEET

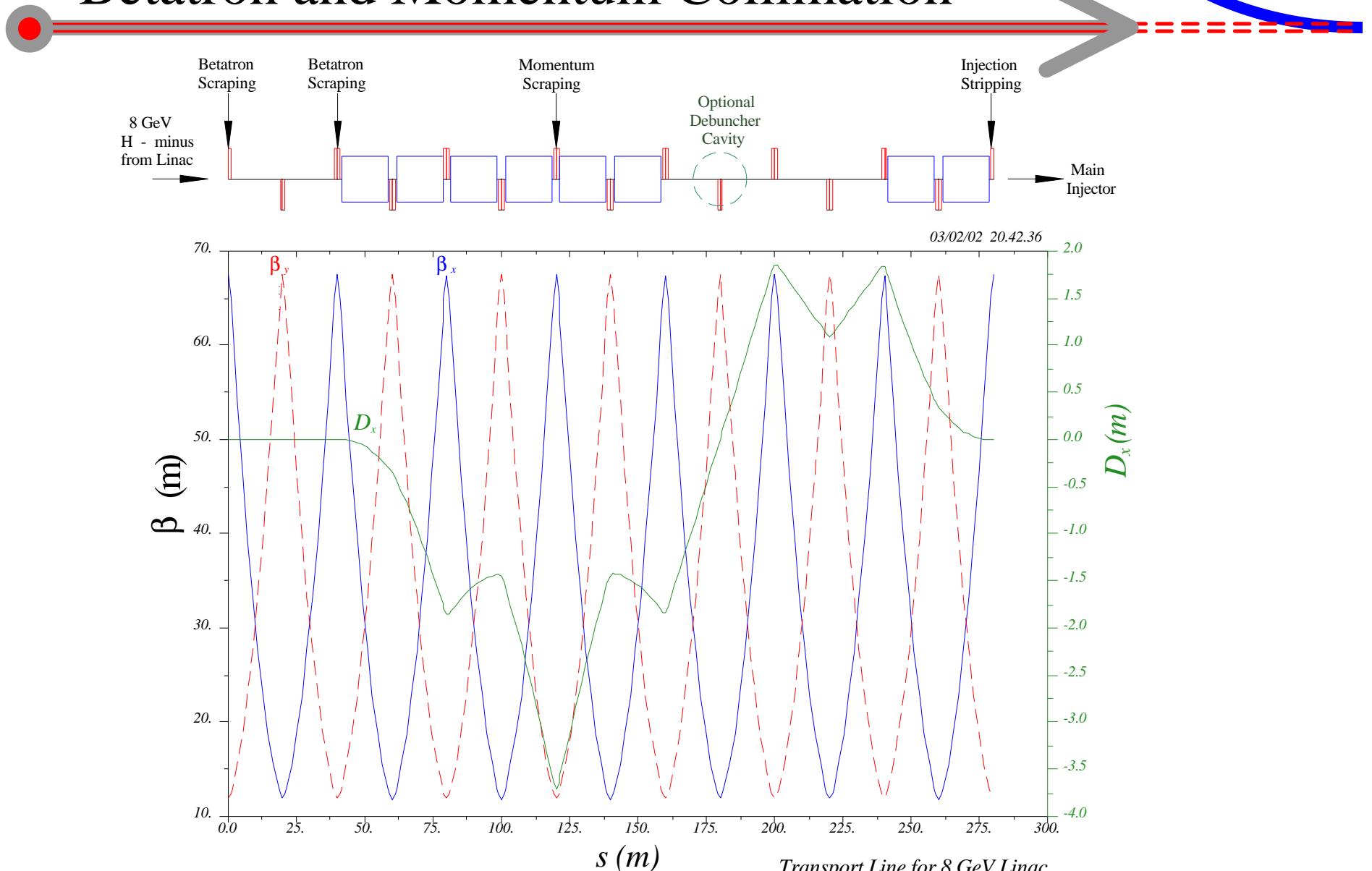
SCALE: 20 0 20 40
1" = 20'-0" VERTICAL FEET

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

8 GEV LINAC STUDY
MI TIE IN PLAN AND PROFILE

DRAWING NO. 6-9-3 TDR-4 REV.

8 GeV Injection Line Optics with Betatron and Momentum Collimation

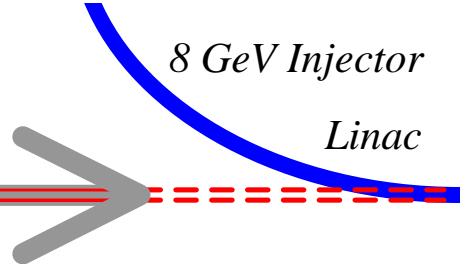


Foil Stripping Collimation of H-

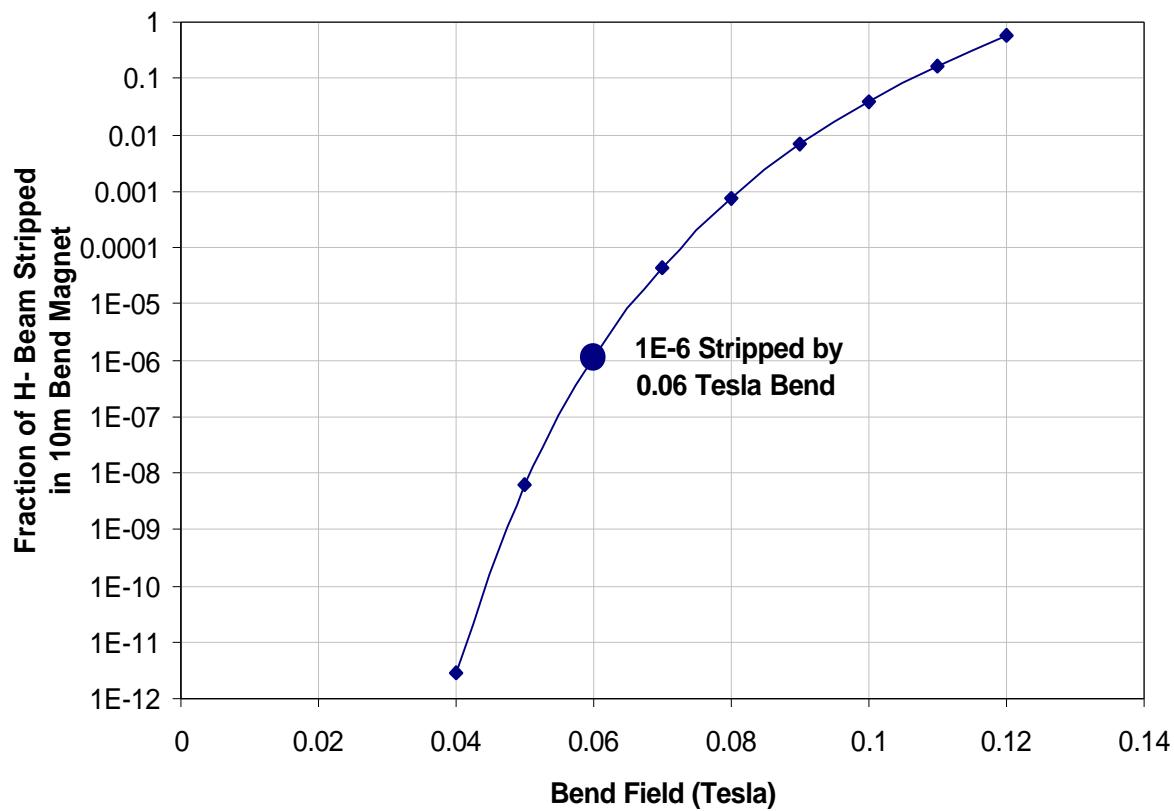


- Traditional collimation schemes incite multiple scattering & showers which result in some “damaged beam” transported down beam channel
- H- ions can be cleanly collimated with foil stripping followed by sweeping magnets
- A beam channel can be designed (BNL/SNS) which is incapable of transporting halo or off-momentum beam, (or damaged beam).

8 GeV H⁻ Stripping in Magnets

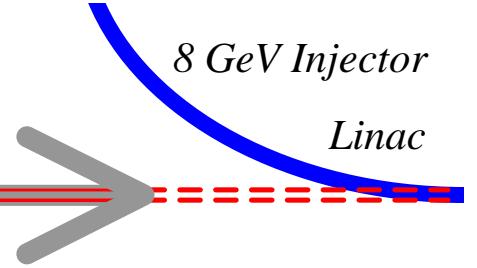


H- Stripping at 8 GeV by 10m Bend Magnet
Ref: sect 7.1.7 (p.438), Handbook of Accelerator Physics & Engineering

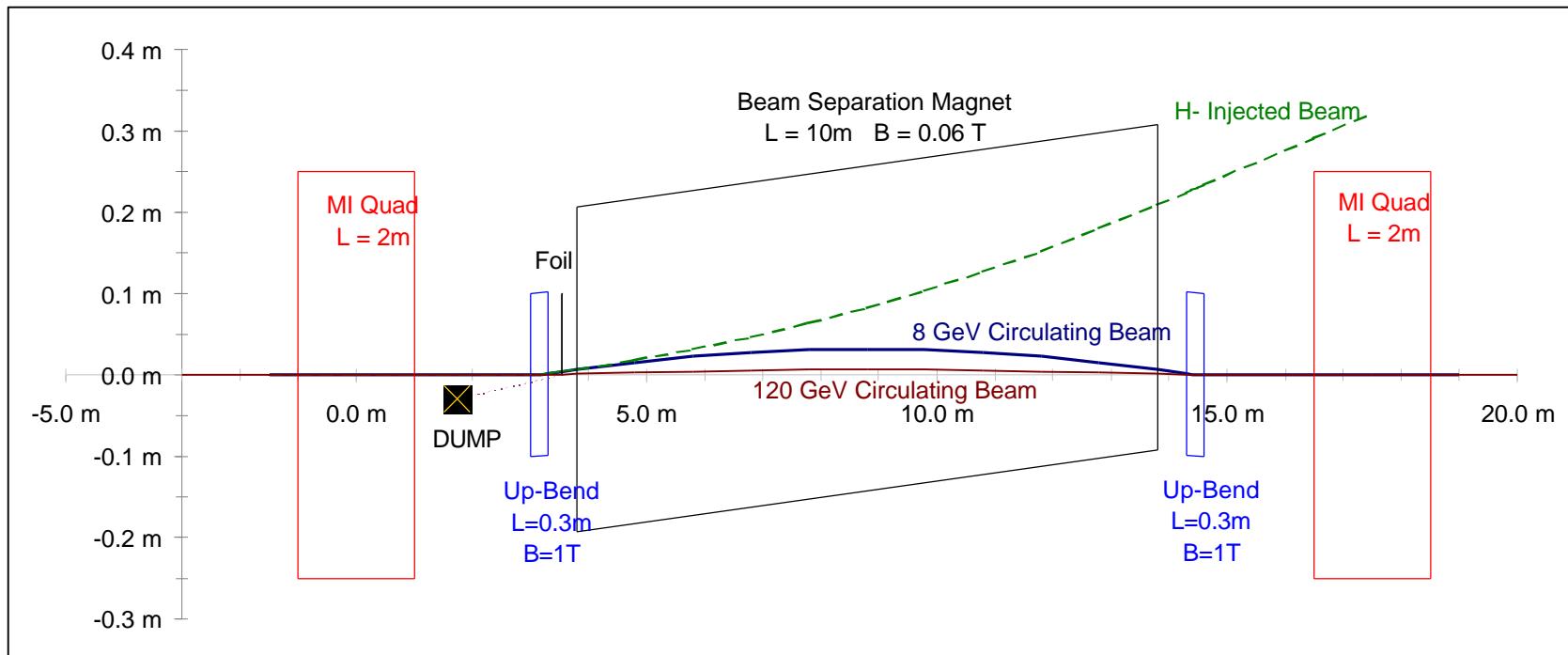


- $B = 0.06$ Tesla strips only $1E-6$ of Beam in 10m length
- 500m Bend Radius is OK
- Stripped Beam Power is < 1 Watt

H⁻ Injection Layout Example



- Foil Stripping Injection at 8 GeV
- Slow orbit bump disappears as beam accelerates
(fast, smaller orbit bump also required to escape foil)
- Injected beam misses nearest quad in MI straight section



H- Injection Painting

(A. Drozhdin)

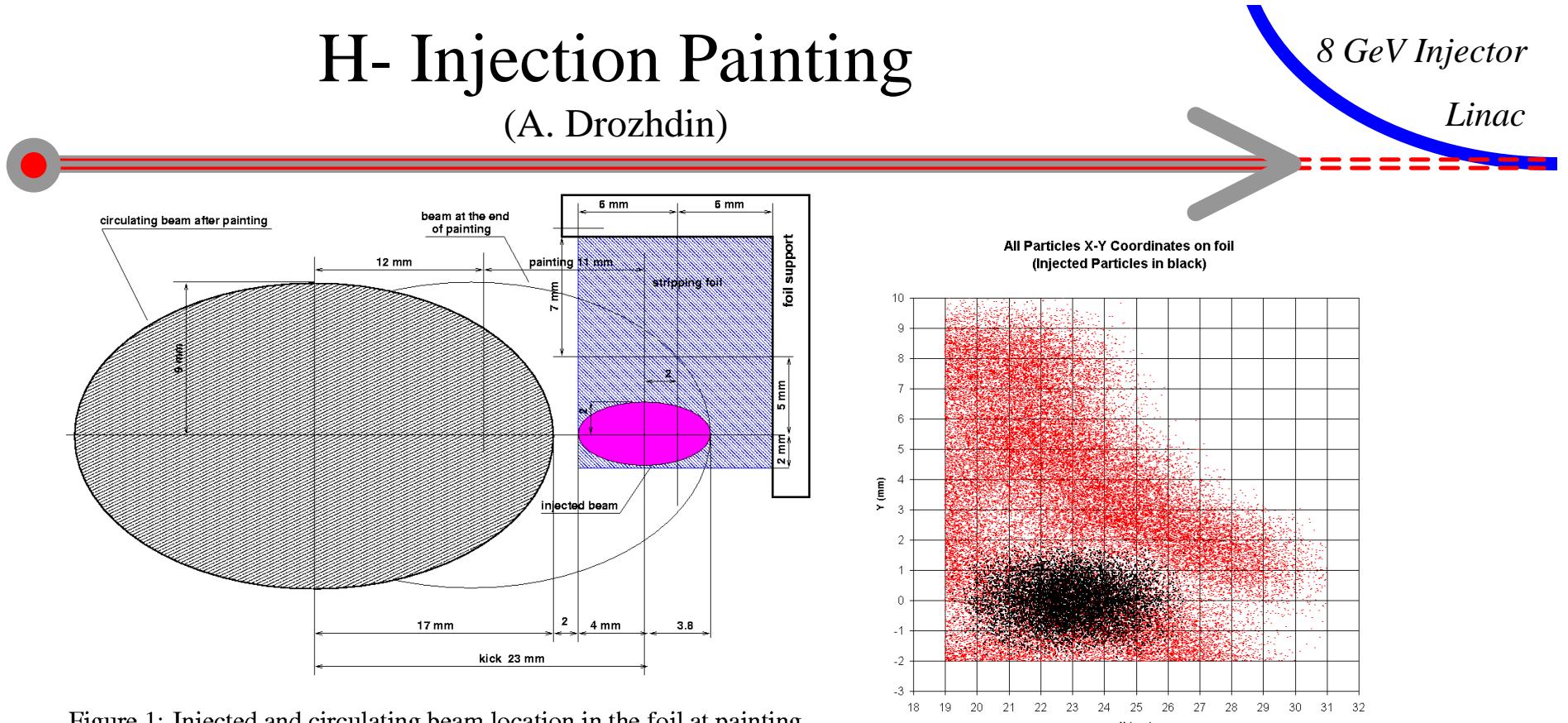
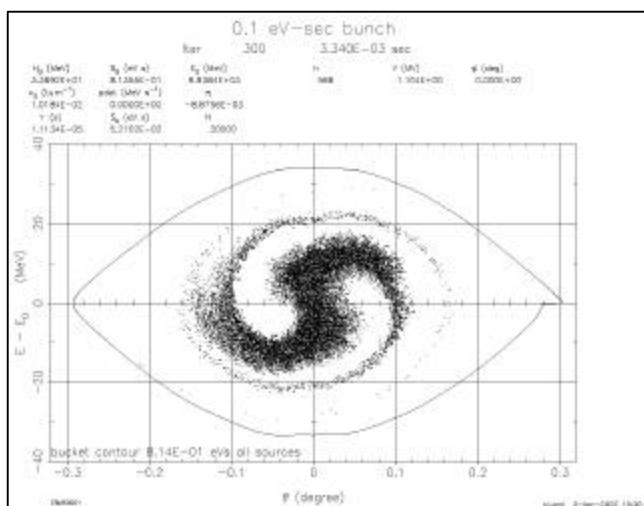
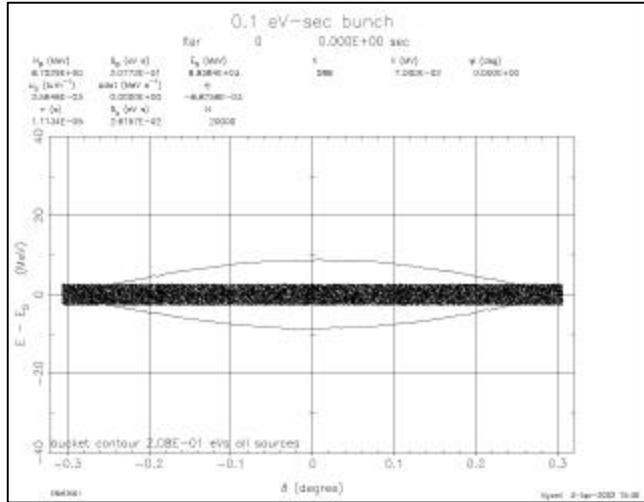


Figure 1: Injected and circulating beam location in the foil at painting.

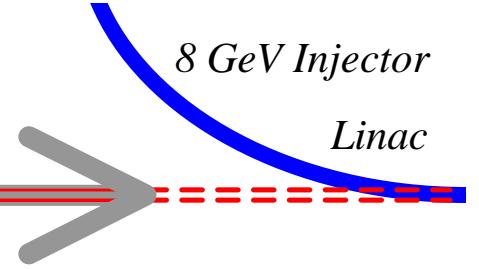
- Painting from 2π into 40π with 90-turn injection seems feasible
- Peak foil temperature ~ 2300 degC
(tolerable with new diamond foils from BNL)

Adiabatic Capture vs. Chopping



- Adiabatic Capture at 8 GeV (no 53 MHz RF chopping)
- We are less sensitive to injection losses than SNS's (since $E_{\text{INJECTION}} \ll E_{\text{FINAL}}$)
- We have more time for Adiabatic Capture (100 ms)
- Simulations (K. Koba) indicate very high capture efficiency in shorter time.

SECONDARY MISSIONS



- Main Mission: “Super-Beams” in Main Injector
- Possible Secondary Missions:
 - 1) 8 GeV Neutrino Program
 - 2) 8 GeV Spallation Neutron Source
 - 3) 8 GeV Fixed-target Program
 - 4) ν -factory front end
 - 5) Electron Linac
 - 6) XFEL
 - 7) Recirculating microtron (pseudo-CEBAF)
 - 8) Pbar Deceleration
 - 9) TESLA damping ring preaccelerator linac

...etc... etc... etc...

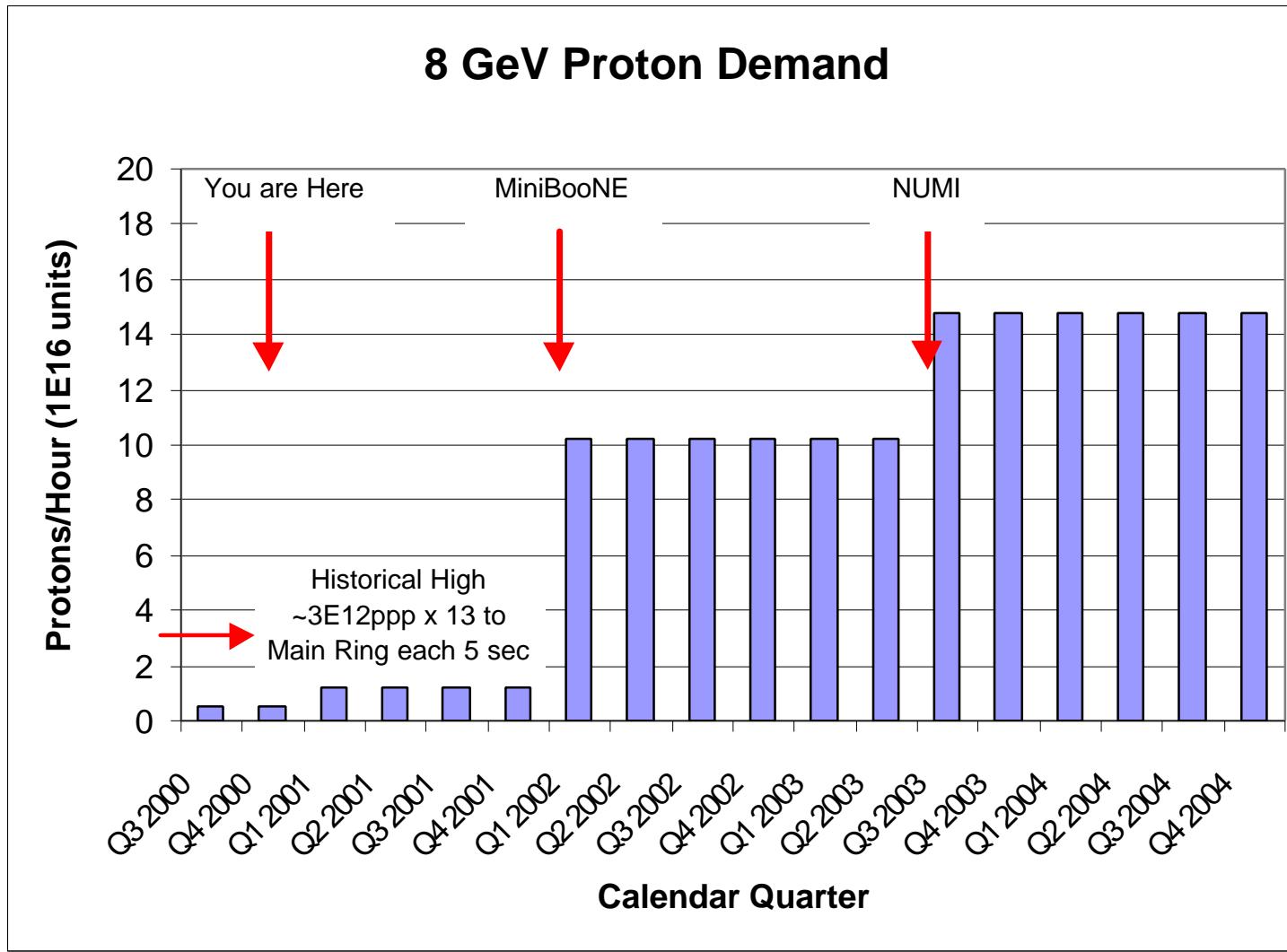
Possible Secondary Mission #1:

8 GeV Neutrino Experiments



- 8 GeV beam for Mini-BooNE follow-on
- Interleave one 8 GeV cycle(s) with MI filling
 - > 3.6E17 Protons/hr to *both* MI and BooNE
- Upgrade potential for >10 MW of 8 GeV beam
- ~ 20% efficiency wall power → beam
 - *Mini-BooNE confirms the LSND result, the 8 GeV linac could help increase statistics >20x.*

Demand Schedule for 8 GeV Protons



Possible Secondary Mission #2:

8 GeV Spallation Neutron Source



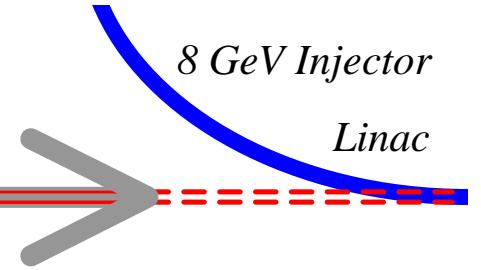
- Upgrade RF Duty cycle from 1% to ~5%
 - RF, couplers, and cryo pipe sizes must anticipate this
- Add SNS-Style Accumulator Ring (R ~ 50m)
- Biggest incremental cost will be Target facility

8 GeV Linac has the potential be competitive as a pulsed neutron source, if FNAL is interested...

(Installed Klystron peak power ~300MW vs. ~50 MW in SNS)

Possible Secondary Mission #3:

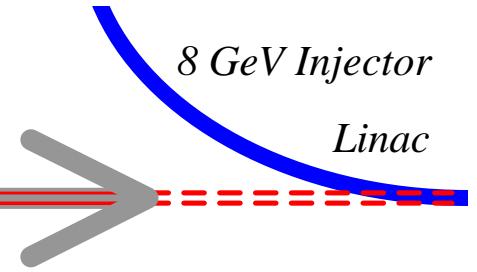
8 GeV Fixed-Target Program



- Pion production per incident beam energy is maximized at ~ 6 GeV (*N. Mokhov*)
⇒ Best source for precision μ , K experiments.
- The RF time structure (~ 50 psec bunches) would allow high-quality TOF separation of neutral K's
- The Recycler might be used as 8 GeV stretcher ring to provide \sim continuous beams of protons.

Possible Secondary Mission #4:

Neutrino Factory



- Very Similar to 8 GeV Spallation Source
(but shorter time spread on target)
 - Possible to use same linac to re-accelerate the muons after filling the accumulator ring?
 - 1) use linac to fill the 8 GeV accumulator for ~1 msec.
 - 2) rephase the cavities for muon acceleration (~0.2 ms).
 - 3) bunch the accumulator beam and extract onto target.
 - 4) debunch & cool the muons in couple μ sec
 - 5) reaccelerate the muons in *same* linac at 8 GeV/turn.
- *everything uses DC magnets.*

Possible Secondary Mission #5:

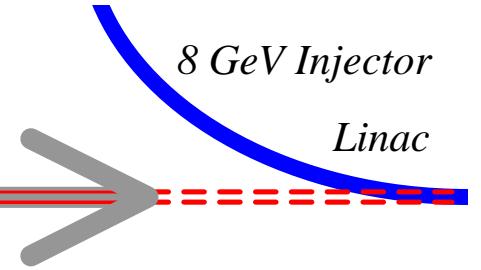
8 GeV Electron Linac



- At least 7 GeV of the linac can accelerate e^-
 - electrons run on-crest, so the gradient will be higher
 \Rightarrow 9-10 GeV e-beams
- Re-phase the cavites for (multiple) pulses of electrons between proton injections to FMI.
 - Many possible physics missions, test beams, etc.
 - Smaller activation problems than proton beams
- An 8-GeV Linac and SCRF infrastructure makes FNAL a good site for a super-B-factory...

Possible Secondary Mission #6:

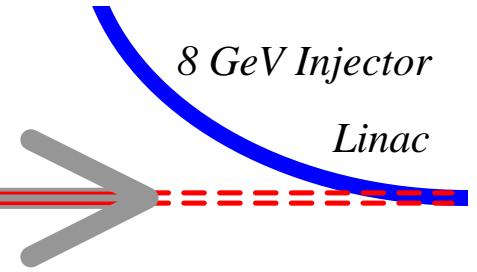
X-ray Free Electron Laser (XFEL)



- There may be competition for XFEL's in the U.S.
- FNAL may want to stay out (or collaborate).
 - Concept of joint ANL-FNAL-DESY project, (sister XFEL's at DESY and FNAL), with ANL taking the lead on US XFEL user facility...?

Possible Secondary Mission #7:

Recirculating Electron Linac



- A CEBAF-Style Recirculating Linac could be made with $\sim 8 \text{ GeV}$ per pass
- Smaller Duty Cycle than CEBAF, but higher energy per pass.
- Either MI or MR tunnels could hold stretcher ring to provide \sim continuous beams of *electrons*.

Possible Secondary Mission #8:

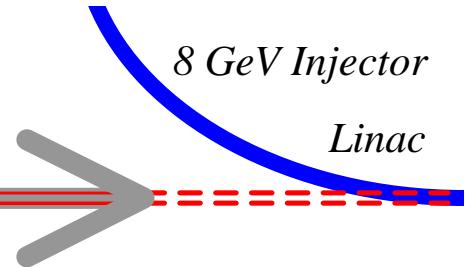
Antiproton Deceleration



Scenario:

- 1) Electron-cool Antiproton Beams in Recycler
 - 2) Ultra-cool core can be frictionally dragged away and separately extracted
 - 3) Small emittances will decelerate efficiently in large-aperture SC Linac
- ⇒ World's best source of “stopped” antiprotons

VLHC and the 8 GeV Injector



- The small beam emittances obtainable with the 8 GeV Injector will make FNAL *by far* the best VLHC injector.
- Small Emittances \Rightarrow Small Beam Currents at fixed Luminosity
 - \Rightarrow Small Stored Energy in Beams
 - \Rightarrow Small instability problems in small beam pipes (\Rightarrow Small magnets)

	Emittance	Luminosity	Beam Current	Stored Energy
VLHC Design Study	10 pi	1.00E+34	180 mA	2.8 GJ (8x LHC)
w/ 8 GeV Injector	0.5 pi	1.00E+34	40 mA	0.6 GJ (2x LHC)

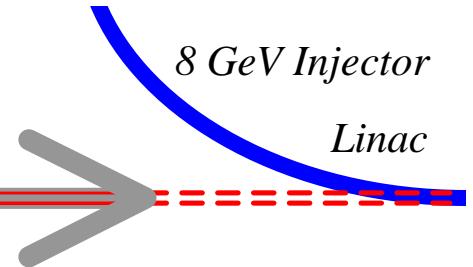
Proton Driver vs. 8 GeV Injector



- There is little doubt that, in principle, a synchrotron is cheaper.
- If we are manpower limited: an 8 GeV Linac has many fewer parts to design than a new Booster Synchrotron.
- The 8 GeV linac will probably be simpler to operate.
- The 8 GeV linac is more likely to produce smaller emittances, if that is the primary goal.
- It can accelerate electrons, and so has a broader range of uses.

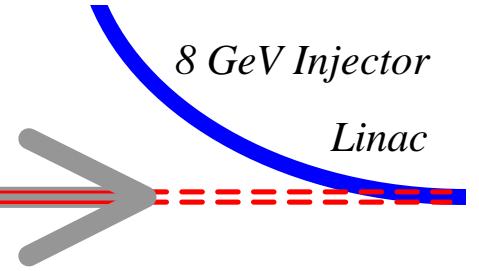
Difficulty with reconciling Proton Driver with B&B subpanel recommendations can be finessed by 8 GeV Linac.

The Linear Collider & 8 GeV Injector



- If the plan is the LC, will be an advantage in asking for this \$7B project to have already completed a *~1% proof-of-principle facility* showing that we understand the performance and costs.
- However in the current political climate, it may be *difficult to ask for a \$100M+ proof-of-principle* facility as the *leading edge of a \$7B project* (GWF opinion).
- FNAL needs a construction project ~ 2005 when NUMI & LHC money starts vanishing. *Need to get a project into the pipeline NOW.*
- The 8 GeV linac has *good, stand-alone physics missions* and will simultaneously *provide \$200M+ “LC R&D” funds* to demonstrate that we understand the performance and economics of big linacs.
- Since *only the TESLA design can accelerate protons*, it simplifies the LC technology choice, which can be made promptly and without contentious technology and cost comparisons.

Many Other Users of SCRF Linacs



SCRF MACHINE PARAMETERS (from JLab LLRF Conference*)

RF Parameters	Units	SNS	RIA	TESLA	12GeV CEBAF	ERLs	FEL	SPL	ELBE	
f_RF	MHz	805	57.5-805	1300	1500	1300 / 1500	749	352	1300	
Eacc	MV/m	10, 16	3, - 10	25/35	18 to 21	20	7.5	3, -9	1 -10	
Q_loaded		7.E+05	>2E7	2.E+06	3.E+07	2.E+07	1.E+07	2.E+06	2.E+07	microphonics minimization is critical to pushing up QI in lightly beamloaded machines
beta		.61/.81	0.49/.61/.81	1	1	1	1	0.5 - 7	1	
Macro-pulse rf	msec	1.3		1.4				4		
Macro-pulse beam	msec	1		0.94				2.3		
Repetition Rate	Hz	60		5, 10				50		
Duty Cycle		0.08	cw	0.007	cw	cw	cw		cw	
Lorentz force coef.	Hz/(MV/m) ²	spec 2, <4 now	spec 2, <4 now	1	1 to 3	1 to 3	1 to 3	2 (LEP)	1	open issue with SNS
Beam Current, ave Macro	mA	26	0.3	9.3	0.4	~0 (<0.2)	5 to 10	13	1	FEL current is understood as unmatched beam current
Beam Phase	Degrees	-20	-30	-3	0	360	-20	-20		
Number of cavity/klystrons		1	1	36	1	1?	1 ?	1 to 4	1	unclear where 1:1 tradeoff lies if performance spread of cavities is small or not in question
Number of cells/cavity		6	6	9 to 18	7	9 or 7	3		9	
Microphonics(meas.)	rms Hz	10		3 to 7	3.5			?	?	clarify low end of frequency spectrum to discount easily tracked slow drifts
Pressure sensitivity				+ 10 Hz/mb				~10		near klystron saturation, slow drift effects influence tuner operation need and control headroom
Nearest mode	MHz delta	0.8	0.8	0.8, 0.3 superstructure	1?	0.8	0.8	0.7		
System Requirements										
Microphonics	rms Hz	15	<5	10	3.5	<<1!	2	10		
Amplitude stability (cor)				2.00E-04	1.10E-05	1.00E-04	1.00E-05			
Amplitude stability (uncor)		0.005	0.01	0.001	2.00E-04	2.00E-03	6.00E-05	0.005	0.05	
Phase stability	degrees	0.5	1	0.5	0.1	0.5??	??	0.5	1	
Klystron saturation	%	obscure accounting	??	3	10, under most extreme conditions	20	0		20	do SELs have a gain/noise advantage when operating near saturation? How do different machines deal with this?
Vector sum calibration	Degree / %			1 and 10						
Resonance Control - Slow	Hz	?		p/m 50	-2					deadband
Resonance Control - Fast	Hz	100		p/m 200	25					6*microphonics + 2* deadband
Beamloading fluctuations	%	1.2 @ 30 kHz		1	NA	2 (inj most critical)	2			Low freq

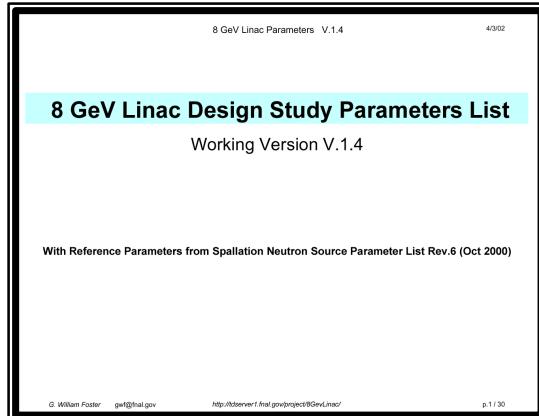
* <http://www.jlab.org/LLRF/Finalagenda.html>

The Linear Collider & 8 GeV Injector (cont'd)



- **If TESLA is approved in the next couple of years,** then the 8 GeV Injector gives the US the opportunity to extract some benefit from our contribution to SCRF Linac technology.
(makes it easier to argue for a US contribution to TESLA if there is a simultaneous construction project with related technology in US)
- **If TESLA is NOT immediately approved,** and only TTF-2 and the 8 GeV Injector are completed, then by ~2009 this will leave the US holding the *strongest technological position to bid for the LC.*
(and 8 GeV linac can be used for TESLA Damping ring pre-acc.)
- The 8 GeV Linac holds the best promise of retaining the current construction slots in HEP (namely NUMI and the LHC), while remaining true to the strategic vision of the B&B subpanel.

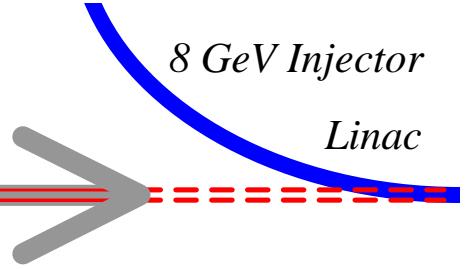
PROJECT INFORMATION



- 30 Page Parameter List (v1.8)
- (Soon) Cost Estimate Spread Sheet w/ BoE
- ~ May 15th - Design Study Final Report
(delayed by Run II Travails...)

<http://tdserver1.fnal.gov/project/8GeVlinac>

CONCLUSIONS



- An 8 GeV Injector Linac will be a useful component at FNAL no matter what future machine is built.
- There are no technical difficulties, just further optimizations. Can copy existing designs.
- It should make FNAL complex simpler to run.
- The cost will be similar to the Main Injector and Proton Driver.